On the Structure of Multi-thread Bouclé Yarn

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Abstract

This research had two dimensions. The first one was theoretical and the geometry of doubled fancy yarn, including bouclé yarn, was modelled mathematically. As a result, the length of the effect component that is necessary to make a copy of those types of fancy yarn was estimated. Further, a geometrical model for the width of the effect-thread helices in the First Spinning Zone was presented. One important benefit of this model was using it to control the structure of the bouclé yarn and to prevent the formation of faults and loops on the bouclé yarns.

The second dimension was experimental. The mathematical, geometrical model of doubled fancy yarn was tested and the coefficient of correlation between the predicted values and the actual values was r=0.90. This was accomplished by providing methods and roadmaps to help making copies of the bouclé and semi-bouclé fancy yarns after using the output of the geometrical model of the structure. Further, it was found that the technological factors which affected the bouclé yarn structure and geometry were the bending stiffness of the effect thread(s), the rotational speed of the hollow spindle, the level of Tension of the core thread, the overfeed ratio, the number of wraps, and the interaction between those factors. Furthermore, when narrow effect helices have formed in the First Spinning Zone, the thickness of the effect thread was as important as its bending stiffness.

To measure the bending stiffness of the input threads, the Beam Method was applied using a simple apparatus, called the Bending Frame, which was built for this purpose.

Dedication

To my father, mother & siblings and their families.

To all those who gave me support while doing my PhD.

To my friends in my hometown, in Syria, and in other countries.

To my fellow Syrian textile engineers who studied textile engineering with me at Damascus University (Syria).

To all my friends and colleagues at Heriot-Watt University

To all my friends whom I met in the UK

Malek Alshukur

الإهداء

أقدم إنجازي العلمي هذا لأبي أحمد و أمي حياة و إخوتي و أخواتي نوال و يامن و محمد و نور و علي و عبير و يوسف و أسرهم.

وأيضاً أهدي هذا الإنجاز لأصدقائي و أصحابي في سوريا وبقية الدول العربية ، و زملائي مهندسي الغزل و النسيج المسالمين في سوريا أو خارجها.

و أهدي هذا العمل إلى كل الذين وقفو بجانبي و منحوني تمنياتهم الطيبة سواء أكانو في سوريا أو خارجها.

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About the Author

<u>Qualifications:</u>

The author studied textile engineering at the Department of Mechanical Engineering of Textile Industries and their Technologies which is part of the Faculty of Mechanical and Electrical Engineering of Damascus University (Syria) and graduated in 2006. He also studied MSc in International Business Management at the Higher Institute for Administrative Development (HIAD) of Damascus University (Syria) in 2008. Following this, he was awarded a Master's Degree in Textiles from Heriot-Watt University (UK) in 2012.

<u>Publications:</u>

The author has the following peer-reviewed articles:

1. Alshukur, M. and Gong H., **Structural Modelling of Multi-thread Fancy Yarn**, *International Journal of Clothing Science and Technology*, accepted.
2. Alshukur, M and Sun D., **Investigating the effect of the core thread tension on structure and quality properties of multi-thread bouclé yarn**, *Indian Journal of Fibre and Textile Research*, Vol. 41(4), pp. 367-372.
3. Alshukur, M. and Fotheringham, A., **Quality and Structural Properties of Multi-thread Fancy Yarn by Using the Design of Experiments**, *Journal of the Textile Institute*, V. 106 (5), pp. 490-502, 2015.
4. Alshukur, M., **Textiles and the Textile Research and Industries in the Twenty-first Century**. *Journal of Textile Science & Engineering* 2014. S2: 005.
5. Alshukur, M. and Fotheringham, A., **Role of False Twist in the Manufacturing Process of Multi-thread Fancy Yarn on Hollow Spindle Spinning Machines**, *Journal of the Textile Institute*, V. 105 (1), pp. 42-51, July 2013.
6. Alshukur, M. **The Quality of Fancy Yarn: Part II: Practical Experiments and Application**, *International Journal of Textile and Fashion Technology (IJTFT)*, Vol. 3(1), pp. 25-38, March 2013.
7. Alshukur, M. **The Quality of Fancy Yarn: Part I: Methods and Concepts**, *International Journal of Textile and Fashion Technology (IJTFT)*, Vol. 3(1), pp. 11-24, March 2013.

Work Experience:

The author worked as a Production Engineer for the textiles industry in Syria for a year. He also worked as a Technician for the Department of Mechanical Engineering of Textile Industries and their Technologies (Damascus University) for a year, then became a Reader (Lecturer Assistant) at the same department for a year.

Glossary of Terms for this Research

There are several terms used in this research which are generic, while some others may have more than one term to describe the same thing.

Term	Definition or Description
Back-doubling (in rotor spinning)	(1) The process of forming a continuous fibre ring in the groove of a rotor where a thin layer of individual fibres is deposited in the rotor groove for each revolution of the rotor. (2) The number of fibres formed by the aforementioned process [1].
Beam Bending Theory	Also known as **Euler-Bernoulli beam theory**, **engineer's beam theory** or **classical beam theory**. A theory that provides a means of calculating the load-carrying and deflection characteristics of beams.
Bending stiffness	also known as **flexural rigidity**, **bending rigidity** or **flexural stiffness**; a term which relates the curvature of bending (i.e. the amount of bending deformation) to the internal force which causes it (i.e. the bending moment) in a linear relationship. The bending stiffness (B) is the product of Young' modulus (E) of bent material and the second moment of area (I) of the same bent material about the axis of bending; i.e.: $B=EI$ [2].
Binder of fancy yarn	This component is the third component of most types of fancy yarn. It is usually a thin multi-filament or in rare cases can be a spun yarn. The function of this component is to fasten the structure of the fancy yarn by fastening the effect component to the core component.
Bouclé yarn	A compound yarn comprising a twisted core with an effect yarn combined with it so as to produce wavy projections on its surface [3]. In the context of this study, bouclé profile and semi-bouclé profile may have a circularity ratio in the range CR= 50 ~90 % [4]. Bouclé yarn is a traditional type of fancy yarn.
Circularity Ratio of Fancy Profile (CR)	The Circularity Ratio of Fancy Profile is a description of the circularity or the roundness of the representative projection of the fancy profile when it is observed under a microscope [4].
Coercive or	It is the bending moment required to overcome the initial frictional

frictional couple in a yarn bending hysteresis loop	resistance due to the inter-fibre friction at fibre contact points within the yarn structure [5]. The coercive couple is given by half-width of the hysteresis loop at zero curvature [6].
Core component of fancy yarn	Also known as **the basic component**, **the foundation component**, or **the ground component** of fancy yarn. It is the component of the fancy yarn which supports the fancy yarn structure and the effect components. The core component may also help in forming the effect of the fancy yarn from the effect component. The core component may be one or two thread, whether these are singles, ply or multi-filament.
Digital Image Processing	The term digital image processing refers to the manipulation of an image by means of a processor. The different elements of an image-processing system include image acquisition, image storage image processing and display. A digital image is basically a numerical representation of an object [7].
Effect component of fancy yarn	It is the component of the fancy yarn which gives the fancy yarn its unique structure, colour and/or texture or all. The effect component may be made of loose fibres or drafted fibres or be one, two or three thread, whether those are singles, ply or multi-filament.
Elastic bending stiffness in a yarn bending hysteresis loop	It is the slope of the bending moment-curvature curve [8]. In practice where the hysteresis loop is not uniform, the elastic bending stiffness is given by the mean slope of the linear regions of the two sides of the hysteresis loop [6].
Fancy arc yarn	A traditional type of fancy yarn which has effect profiles which take the shape of small arcs on the yarn surface[1].
Fancy Bulkiness of Fancy Yarn	Also known as the Fancy Bulkiness of Fancy Profiles. A term which is measured chiefly by the ShF and secondly by the RSI.
Fancy profile	A term which refers to the effect projection on the fancy yarn surface.
Fancy yarn	Also known as **novelty yarn** or **effect yarn**. A yarn that differs from the normal construction of single and folded yarns by way of

[1] This definition was put forward by the author of this thesis and was presented depending on the author's understanding of this type of fancy effect profiles, thus it is not available elsewhere.

	deliberately produced irregularities in its construction. These irregularities relate to an increased input of one or more of its components, or to the inclusion of periodic effects, such as knops, loops, curls, slubs, or the like [3].
Fibre migration	A change in the distance of a fibre or filament from the axis of a yarn during production [3].
First Spinning Zone on hollow-spindle machines	The First Spinning Zone is located between the supply rollers of the effect threads and the in-let hole of the hollow spindle.
Gimp yarn	A yarn made of one or more strands twisted around a usually finer central ground yarn and overfed to form a clear spiral wrapping [3]. Gimp yarn is a traditional type of fancy yarn.
Informativity of regression model[2]	The Akaike information criterion (AIC) is a measure of the relative quality of statistical models for a given set of data. Given a collection of models for the data, AIC estimates the quality of each model, relative to each of the other models. Hence, AIC provides a means for model selection. The model that is chosen will be the one which is most probable to minimize the loss of information, due to the usage of each of those models to represent the same data.
Input yarns of a multi-thread fancy yarn	It will be called "threads" in this research to distinguish it from the word "yarn" which will be used to mean the final fancy yarn. Therefore, the final fancy yarn will be called a "multi-thread fancy yarn" instead of a "multi-yarn structure fancy yarn" or "multiple yarn structure fancy yarn".
Irregularity ratio (*U*%) and CV_m%	A measure of the evenness of the cross section of spun yarn. This ratio stands for the mean linear irregularity, while the coefficient of variation of mass (CV_m%) stands for the mean square irregularity [1].
Isotropic material	A material that its properties, in particular the mechanical properties, are independent of the direction of loading [9].
Loop yarn	A compound yarn comprising a twisted core with an effect yarn

[2] This definition was taken from Wikipedia at https://en.wikipedia.org/wiki/Akaike_information_criterion

	wrapped around it so as to produce wavy projections on its surface. Loop yarns have well-formed circular loops projecting from the core [3]. In the context of this study, the Circularity Ratio of Loop Profile may be the range 85~l00 % [4]. Loop yarn is a traditional type of fancy yarn.
Morphological Image Processing	Morphological image processing describes a range of image processing techniques that deal with the shape (or morphology) of features in an image. Morphological operations are typically applied to remove imperfections introduced during segmentation. In the context of mathematical morphology, morphology as a tool of extracting image components that are useful in the representation and description of region shape such as boundaries, skeletons etc. The goal of morphology operations are simplify image data, preserve essential shape characteristics and eliminate noise [10].
Nep	A small knot of entangled fibres. In the case of cotton it usually comprises dead or immature cotton hairs [3].
Neps (+140%, +200%, +280% or +400%)	The count of all neps on a yarn on the basis of a nep 1 mm long having an average cross section 1.4 ×, 2 ×, 2.8 × or 4 × the mean cross section of the yarn [11].
Number of Fancy Profiles (N)	The number of the fancy profiles (i.e. the effect profiles or projections) of any fancy yarn is the number of the main fancy profiles of the effect component in a unit length of the fancy yarn (usually one meter). It does not include the number of any other type of fancy profiles if they exist as secondary or companion profiles over the fancy yarn surface [4].
Number of wraps of the binder	It may also be called **the binder wrapping density**. Although it is not twist, many researchers called it "**the fancy yarn twist**" [12-18].
Orthogonality of the Experimental Design	Two effects (or responses) are orthogonal if neither estimated effect is affected or biased by the other. In an experimental design, if two columns of (+1)and (-1) coded numbers have the property that the sum of the products of their respective terms is equal to zero, the columns are orthogonal and the estimated effects based on those columns are orthogonal [19].
Packing density of	The way in which fibres are packed or distributed within the cross-

(staple) spun yarn	section of spun yarn. In a theoretical model, cylindrical fibres may have open packing where fibres lie in layers between successive concentric circles, or fibres may have hexagonal close packing [11].
Pattern in fabric (fault)	Periodic fault in a cloth appears as an (unfavourable) pattern due to a periodic fault the constituent yarns.
PET	Polyethylene terephthalate.
Periodic variations in the linear density of spun yarn	Those faults may be classified according to their wavelength in comparison to fibre length to [5]: • Short term variation which is 1~10×fibre length; • Medium term variation which is 10~100× fibre length; and • Long-term variation which is 100~1000× fibre length.
Pure bending	The case of pure bending is related to a straight beam of uniform cross-section, when subjected to end couples *M* applied about a principal axis, bends into a circular arc of radius *R*. When the beam is also subjected to shearing forces in addition to bending moments, the axis of the beam is no longer bent into a circular arc [2].
Quality parameters of fancy yarn	The basic quality parameters of multi-thread fancy yarn, including bouclé and semi-bouclé yarns, are the Size (or Area) of Fancy Profile (A) , the Number of Fancy Profiles (N) , the Circularity Ratio of Fancy Profile (CR), the Shape Factor of Fancy Yarn (ShF) and the Relative Shape Index of Fancy Yarn (RSI) [4].
Quality parameters of bouclé yarn	The basic quality parameters of multi-thread bouclé and semi-bouclé yarns are the Size (or Area) of Bouclé Profile (A) , the Number of Bouclé Profiles (N) , the Circularity Ratio of Bouclé Profile (CR), the Shape Factor of Bouclé Yarn (ShF) and the Relative Shape Index of Bouclé Yarn (RSI).
Random variation in a (manufacturing) process	Also called **natural variation**, **background noise**, **common-cause variation**, **chance-cause variation** or **non-assignable-cause variation**. This kind of variation is inherent in the process or embedded in the system, and is caused by the interplay of multiple minor variables in the process [20, 21]. So, this kind of variation is chronical, unavoidable. Further, a process that is operating with only chance causes of variation present is said to be in statistical control [21]. Random variation is the

	subject of quality improvement while assignable variation is the subject of quality control [20].
Relative Shape Index of Fancy Yarn	The Relative Shape Index of Fancy Yarn refers to the relative fancy bulkiness of the fancy yarn effect profiles; the higher the value of the RSI the higher the relative bulkiness of the fancy yarn. Accordingly, if there are several similar fancy yarns (either fancy loop yarns or fancy bouclé yarns, etc.), then the bulkier of them is the one which has the higher value of the RSI. The Relative Shape Index of Fancy Yarn is also a dimensional factor and it is given by the equation: $RSI = ShF/T_{tex}$ Where: ShF is the Shape Factor of Fancy Yarn; T_{tex} is the linear density of the fancy yarn, (tex). When the ShF is measure in ($mm^2\ m^{-1}$), and the linear density in tex, the RSI is measured in $mm^2 m^{-1} tex^{-1}$ [4].
Robust design	A product or manufacturing process design is robust if it is relatively insensitive to noise factors which are present [19].
Roving	(1) In spun yarn production, an intermediate state between sliver and yarn. Roving is a condensed sliver that has been drafted, twisted, doubled, and redoubled. The product of the first roving operation is sometimes called slubbing. (2) The operation of producing roving. (3) In the manufacture of composites, continuous strands of parallel filaments [22].
Semi-bouclé profile	It may also be called bouclé-like profile.
Shape Factor of Fancy Yarn (ShF)	The value of the Shape Factor of Fancy Yarn expresses the absolute Fancy Bulkiness of the fancy profiles regardless of the original thickness of the whole fancy yarn. The Shape Factor of Fancy Yarn is a dimensional factor and it is given by the equation: $ShF = N \times A$ where: N is number of the effect profiles in a unit length of the fancy yarn, (m^{-1} or dm^{-1} as convenient); A is the average area (or size) of the effect profile (usually mm^2). Higher values of the ShF mean or indicate larger or greater visual

	effects of the fancy yarns [4]. The ShF is used to compare the Fancy Bulkiness of several fancy yarns when the components have the same thicknesses; any change to the thickness requires the usage of the RSI to do the same job.
Size of Fancy Profile (A)	It also may be called **the Area of Fancy Profile**. It is the average area of an ultimate fitted polygon drawn to match the circumference of the fancy profile [4].
Slub yarn	a yarn in which slubs are deliberately created to produce a desired effect [3]. Slub yarn is a basic type of fancy yarn.
Slubbings	The **slubbings** or **ropings** are the products of the tape condenser following the card in the woollen system of long-staple spinning. They are similar to rovings but without twist because they are made by splitting of the fibrous web delivered by the card into ribbons which are rubbed to impart the required cohesion [11].
Snarl yarn	A compound yarn that displays snarls or kinks projecting from the core [3]. Snarl yarn is a basic type of fancy yarn.
Specific bending rigidity of fibre	Also known as **specific flexural rigidity**. It is the flexural rigidity of a fibre of unit (linear density)^2. It equals (couple/curvature)/(linear density)^2 [23].
Spinning triangle on hollow-spindle machines	The spinning triangle forms when the effect thread emerges from the supply rollers to the point where it starts making a helix around the core thread at the beginning of the First Spinning Zone.
Spiral yarn	A plied yarn displaying a characteristic smooth spiralling of one component around the other [3]. Spiral yarn is a basic type of fancy yarn.
Statically determinate beams	A type of beam where the reactions at the supports can be obtained using the methods of statics. Those types of beams are the simply supported beam, the cantilever beam and the overhanging beam [9].
Statically indeterminate beams	A type of beam where it is not possible to determine internal forces or the reactions at its supports by only applying the principles of statics, i.e. by using the free-body diagram. This this because the principles of statics assume the structures rigid and undeformable, where in reality there are many occasions where beams deform or may have many types

	of reactions at the supports, such as the case of being fixed at one end [9].
Structural parameters of fancy yarn	The structural parameters of multi-thread fancy yarns, including bouclé and semi-bouclé yarns, are mainly the number of wraps (W) of the binder, the overfeed ratio (η) of the effect thread(s), the number of the threads of the structure and the linear densities of these threads.
Structural Ratio of Fancy Profile	The Structural Ratio of Multi-thread Fancy Yarn (SR) is defined as the number of wraps of the binder divided by the overfeed ratio of the effect component. It is given by the equation: $SR = W/\eta$ and it is measured in wrap per metre (wpm). The Structural Ratio of Multi-thread Fancy Yarn is useful to select the number of wraps which is needed to produce a specific type of multi-thread fancy yarn having a definite overfeed ratio. The Structural Ratio of Multi-thread Fancy Yarn is also a measure of the compactness of the fancy yarn structure.
Terry (woven fabric)	a warp-pile fabric in which loops are created, without positive assistance, by varying the relative positions of the fell and the reed. A high tension is applied to the ground warp and a very low tension to the pile warp [3].
Thick places (+35%, +50%, +70% or +100%),	The count of the thick places in a (spun) yarn over a specific length of the same yarn, or over time. The control limit is set either 35%, 50%, 70% or 100% above the average value of linear density. A thick place is counted if the control limit is overstepped [11].
Thin places (-30%, -40%, -50% or -60%)	The count of the thin places in a (spun) yarn over a specific length of the same yarn, or over time. A thin place is counted if the local linear density of the same yarn drops below the control limit which is set either 30%, 40%, 50%, or 60% below the average value of linear density [11].
Velour (woven fabric)	(1) A heavy pile fabric with the pile laid in a single direction. (2) A napped-surface woven fabric or felt in which the surface fibres are laid in a single direction to present a smooth appearance. (3) A terry fabric that has had the tops of the loops cut off in a process subsequent to weaving. It is also known as **cropped terry pile** and

	sheared terry pile [3].
Velvet (woven fabric)	A cut warp-pile fabric, originally of silk, in which the cut ends of the fibres form the surface of the fabric. This effect is produced (1) from a pile warp lifted over wires and cut by a trivet, (2) from a pile warp lifted over wires which are withdrawn to cut the pile, (3) by weaving two fabrics face to face with the pile ends interchanging from one fabric to the other; the pile ends are cut by a knife while still in the loom, giving separate pieces of velvet [3].
Wash-and-wear	Also known as **easy-care**; **drip-dry, minimum-care**; **smooth-drying**. Wash-and wear is descriptive of textile materials that are reasonably resistant to disturbance of fabric structure and appearance during wear and washing and required a minimum of ironing or pressing [3].
Woollen spinning system	Also know as **woolen system** or **condenser system**. It is the fundamental system of making yarns for woolen fabrics. In yarns spun on the woolen system, the fibers are not parallel but are crossed in what appears to be a haphazard arrangement. After blending, fibers produced on the woolen system are evenly distributed in carding on two, three, or even four cards. From here, the split web, called roving, goes to the spinning frame. In addition to wool, manufactured fibers, cotton, wastes, and noils can be processed on the woolen system. In general, the fibers used are shorter and more highly crimped than those used on the worsted system and are of the type that can be fulled [22].
Worsted spinning	A system of textile processing for manufacturing spun yarns from staple fibres usually over 3 inches in length. The main operations are carding, combing, drafting, and spinning. There are three basic systems of worsted yarn spinning: the Bradford (or English system), the French (Alsatian or Continental system), and the American system [22].

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Chapter 1: Introduction

1.1 Definitions and Scope

Fancy yarn was defined by Denton and Daniels [3] as "*A yarn that differs from the normal construction of single and folded yarns by way of deliberately produced irregularities in its construction. These irregularities relate to an increased input of one or more of its components, or to the inclusion of periodic effects, such as knops, loops, curls, slubs, or the like*". While fancy yarns are numerous, this particular study is concerned with bouclé yarn and semi-bouclé yarns.

Bouclé yarn is one of the traditional fancy yarns, and is defined as "*A compound yarn comprising a twisted core with an effect yarn combined with it so as to produce wavy projections on its surface.... Generally speaking, bouclé yarns exhibit an irregular pattern of semi-circular loops and sigmoid spirals*"[3]. Bouclé yarns, gimp yarns and loop yarns belong to the same group of fancy yarn. The difference between them is that the effect profiles on the surface of gimp yarns are corrugations similar to waves, and in loop yarns they are circular loops (i.e. rings), but they are irregular, semi-circular loops in bouclé yarns [3]. More information about these yarns can be found in the Glossary of Terms above. Bouclé and other types of fancy yarn have several peculiarities that make them appealing to fashion designers and give them the advantage over the traditional plain yarns [24, 25]. The combinations of their texture, colour, handle, appearance and performance are the key features of fancy yarns. Aesthetic and tactile features of fancy yarns make them fundamentally different from any other conventional plain yarn [24, 26, 27].

The research on fancy yarns nowadays is more important than it has ever been before. The late period of the twentieth century highlighted new systematic and objective methods of approaching fancy yarns [24]. Those methods were the result of several factors such as the expanding usage of fancy yarns in fashion and clothing, upholstery and other decorative textiles; the introduction of new technologies and machinery; the competition for a respectable share in the market; the desire to reduce costs and maximize the flexibility of textile firms; the introduction of new, sustainable, relatively cheap and hygienic fibres (e.g. bamboo); the determination to increase the knowledge of such important yarns especially their structure, properties, response and performance under different circumstances; and the determination to predict the mutual relationships between those characteristics. If such relationships were identified, the manufacturing processes of fancy yarns will be used more efficiently to meet a particular criterion or to define a specific property of those yarns. Subsequently, those relationship may help in designing the fancy yarns and in optimising their structure and any other further processing stages in weaving or knitting [24].

Since the research into multi-thread bouclé yarns was scarce and limited to a small number of studies, it was important to enrich the body of research related to fancy yarns by studying the structure and manufacturing process of multi-thread bouclé yarns on the hollow-spindle system. A similar study may be conducted on multi-thread bouclé yarns made on other spinning systems.

1.1.1 Multi-thread Fancy Yarn Included in the Study and those not Included in the Study

This study is concerned with the structure of multi-thread bouclé yarn and semi-bouclé yarn. It also relates the structure of multi-thread bouclé yarn to its quality, i.e. quality parameters of fancy yarn as defined by Alshukur [4, 28]. The technology used to make the bouclé yarns and semi-bouclé yarns of this study was the hollow-spindle system.

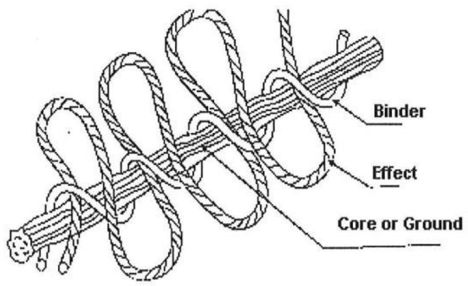
Therefore, this study does not account for:

- bouclé yarns made using drafted fibres, i.e. where the effect component of those yarns is made by drafting slivers or roving;
- doubled bouclé yarns, which are multi-thread bouclé yarns made using the traditional doubling and twisting processes; and
- the various mechanical properties of bouclé yarn.

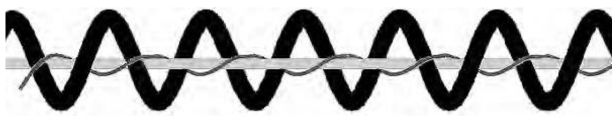
These restrictions do not mean that the type of bouclé yarn studied is more important than bouclé yarns made by drafted fibres, nor do they mean that the hollow-spindle system is more important or more preferable in the industry. The author of this thesis acknowledges that each of those types of bouclé yarn is important and it has its unique characteristics. For example, the majority of fancy yarns made on the hollow-spindle system tend to be bulkier and have lower wear resistance than those made using the traditional ring system [29]. Additionally, the bouclé yarn may have only bouclé profiles when made on the traditional ring and doubling systems, but it may have bouclé profiles, semi-bouclé profiles and sigmoidal sections when made on the hollow-spindle system or the combined system. Since semi-bouclé profiles may exist in the structure along side the bouclé profiles, they were included in this study. For simplicity, the term **bouclé yarn** will be used in this research to mean **multi-thread bouclé yarn which also may have semi-bouclé profiles** unless specified otherwise.

1.1.2 Description of Bouclé Profile and Semi-bouclé Profile

Bouclé profiles usually take the shapes provided in Figure 1.



(a) Section of bouclé yarn having only protruding bouclé profiles. This yarn was made with only one effect thread (reproduced from [30])



(b) Bouclé yarn having a sine-wave bouclé profiles (reproduced from [29])

Figure 1: Structure of Bouclé Yarn Showing Bouclé Profiles

Those profiles are open-based, semi-circular fancy projections. The term "bouclé profile" also refers to a fancy profile which has the shape of one phase of sine wave where the height of this phase is greater than, or equal to, the width of the base of this phase.

The term "semi-bouclé profile" may include:

- U-shaped profiles;
- elongated loop profiles, which may be semi-circular, closed profiles; and
- open-based, flexed bouclé profiles.

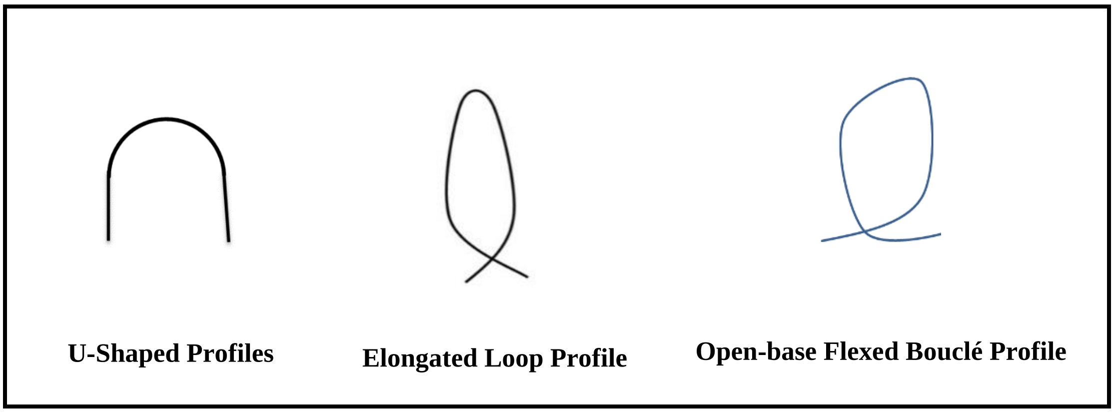


Figure 2: Bouclé-like Profile

Semi-bouclé profiles may also be called bouclé-like profiles. They are better understood by referring to Figure 2. Those semi-bouclé profiles may result on the fancy yarn surface due to three reasons. The first reason is winding of the bouclé yarn on packages. The second reason is internal stresses in the effect thread, e.g. when the effect thread(s) is an unbalanced ply yarn. The third reason is a defective effect thread that has at least a point having relatively low value of bending stiffness which makes the thread bends irregularly.

Not only bouclé projections, but also bouclé and semi bouclé profiles were considered in this study. Bouclé projections are the bouclé profiles which protrude on the yarn surface and can be identified readily. They need no further effort to make sure they exist. They usually attract the attention of an assessor of bouclé yarns. However, there are other types of bouclé profile which exist on the yarn surface, but they do not project over the yarn surface. Instead, they lie on the yarn surface (Figure 3) because of the winding process or due to defects in the effect thread(s). Those lying bouclé profiles are not easily visible. It was possible to check the reason for obtaining the *unapparent* bouclé profiles by a manual attempt to raise such profiles. The reason that they were there was the winding process when those profiles did not collapse back to lie on the structure. Therefore, they were considered while counting the bouclé profiles. However, when those profiles result from defects in the effect thread(s), they normally return back to lie on the yarn surface. Those fancy profiles were not considered bouclé profiles. Subsequently, they were excluded from counting and measurements. Therefore, the *actual* number of bouclé profiles was considered instead of the number of *apparent* or readily visible bouclé profiles or projections. The *actual* number of bouclé profiles includes both the *apparent* and *unapparent* bouclé profiles.

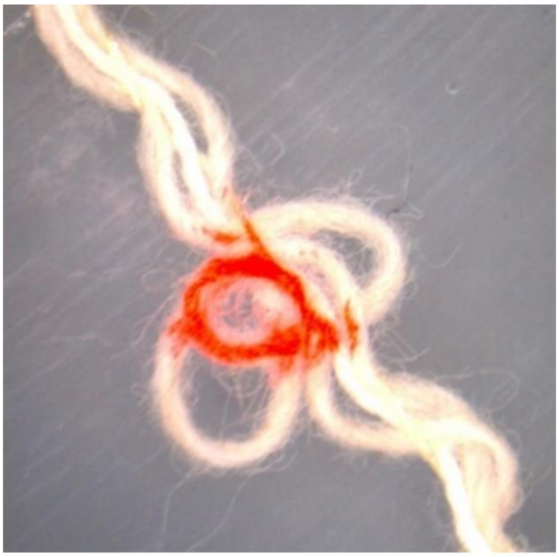


Figure 3: Segment of Bouclé Yarn Showing Two Protruding Bouclé Profiles (or Projections), a Bouclé Profile Lying on the Yarn Surface (Highlighted by Different Colour) and Wavy Sections. This Bouclé Yarn was Made Using Two Effect Threads

1.2 Aims

This research aimed to:

1. Model the structure of multi-thread fancy yarn in general, and use this model to derive a model for the structure of multi-thread bouclé and semi-bouclé yarn, taking into account the technology used to make it.
2. Provide an analytical understanding of the manufacturing process of multi-thread bouclé yarns on hollow-spindle machines and the way in which such a manufacturing process affects the structure of those yarns.
3. Study the influence of input thread thickness and bending stiffness, on the structure and quality of multi-thread bouclé yarns.
4. Study the technological factors of the hollow-spindle machine and their influence on the structure and quality parameters of bouclé yarns.
5. Study the relationship between the structural parameters and quality parameters of bouclé yarns.

1.3 Objectives

To achieve Aim 1 of this research, it was required to:

1. Introduce a graphical model of the building unit of the structure of multi-thread fancy yarns regardless of the technology used to make; whether it is the hollow-spindle system or through the ring spinning and twisting processes.
2. Use trigonometry and calculus to provide mathematical models for the components of that basic building unit of the structure.
3. Assemble the models of the components of the basic building unit of the structure to obtain a mathematical model of the structure of multi-thread fancy yarns.
4. Modify this form of the model to account for the special case of bouclé and semi-bouclé yarns made using the hollow-spindle system.

To achieve Aim 2 of this research it was required to:

1. Study the First Spinning Zone[3] of the hollow-spindle machine and the geometry of the intermediate product within the First Spinning Zone.
2. Study the factors that may affect the First Spinning Zone. Those factors may be: the rotational speed of the hollow-spindle, the overfeed ratio of the effect thread(s), the number of wraps of the binder, the thickness of the effect thread(s), the number of the effect threads and the bending stiffness of the effect thread(s).

To achieve Aim 3 of this research it was required to:

1. Find a method to estimate the bending stiffness of the input threads.
2. Study the influence of the bending stiffness of the effect component on the structure and quality of bouclé yarn.
3. Investigate the influence of the bending stiffness of the core component on the structure and quality of bouclé yarn.
4. Investigate the influence of thickness of the effect thread on structure and quality of bouclé yarn.

To achieve Aim 4 of this research, it was required to:

1. Study the influence of the spinning triangle[4] on the structure and quality of bouclé yarn.
2. Investigate the influence of the rotational speed of the hollow-spindle on the structure and quality of bouclé yarn.
3. Study the influence of Tension of the core thread on the structure and quality of bouclé yarn.

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[3] The First Spinning Zone is located between the supply rollers of the effect threads and the in-let hole of the hollow spindle.

[4] The spinning triangle forms when the effect thread emerges from the supply rollers to the point where it starts making a helix around the core thread within/at the beginning of the First Spinning Zone.

To achieve Aim 5 of this research, it was required to:

1. Study the influence of the overfeed ratio on the structure and the quality parameters of bouclé yarn.
2. Study the influence of the number of wraps of the binder on the structure and the quality parameters of bouclé yarn.
3. Study the influence of interaction between the overfeed ratio and the number of wraps on the structure and quality parameters of bouclé yarn.

Chapter 2: Literature Review

2.1 An Overview of the Research Related to Bouclé Yarn and Similar Fancy Yarns

The research related to multi-thread bouclé yarns made on hollow-spindle spinning machines is limited to a few studies [12, 13]. Moreover, the largest share of the studies related to multi-thread fancy yarns made on those machines has concentrated in overfed fancy yarns which do not have any commercial designation [14-18, 31-37]. Therefore, those studies will be referred to in this investigation to benefit from them. Additionally, the studies related to bouclé yarns made using drafted fibres on the hollow-spindle system [25, 38, 39] or bouclé yarns made using other methods, such as the ring system or the combined system[5] [12, 13], will be reported.

Such studies, described above, may be divided into three main domains: one that is concerned with the various properties of those fancy yarns. i.e. mechanical, structural, or physical properties, and the factors affecting them [12, 39]. The second domain addresses the behaviour of the fancy yarns, in particular bouclé yarn, in knitted or woven structures [12, 13, 39]. The last one is based on modelling the structural appearance or mechanical properties of those yarns, especially bouclé yarn [25, 27, 40].

To address the importance of the manufacturing processes in shaping the fancy yarns, researchers conducted statistical studies to identify relationships between some of the technological factors of the relevant manufacturing process (or machine) and the geometry and structural properties of fancy yarns [24, 31, 33, 37, 41, 42]). Some of those fancy yarns were manufactured in a one-stage production process using a hollow-spindle spinning machine or the combined system; others were made on a two- or three-

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[5] In the combined system, the hollow spindle is either fitted above the ring spindle in one machine, and in the second form, two hollow spindles are fitted one above the other, without a ring spindle.

stage process. Examples of the fancy profiles studied were bouclé profiles [12, 13] semi-bouclé profiles [14], loop profiles [16, 17, 31], knot profiles [17, 31], spiral profiles [17], snarl profiles [31] and mixed fancy profiles on one fancy yarn structure [16-18, 31], etc. More recently, a few studies were reported about gimp yarns [4, 28, 37, 42].

2.2 Importance of Bouclé and Semi-bouclé Yarns in Knitted and Woven Fabrics

Bouclé and semi-bouclé yarns may have a wide range of application. For instance, bouclé yarns may be used to create “woolly” fleecy fabrics suitable for winter or autumn [29]. Mole and Knox reported that terry-pile bouclé yarns made of drafted fibres may have a wide range of applications in sportswear, leisurewear, pile fabrics for apparel (i.e. terry, stretch terry and towelling), and household fabrics (e.g. bedspreads, etc.) [39]. Other researchers reported the use of fancy yarns (including bouclé yarn) in modern fashion [43], ladies and children outerwear, normal and prestigious fashion clothing, curtains, upholstery, wallpaper [34], knitted and woven fabrics [32, 35, 44], furnishings and decorative textiles, e.g. those which are used in hotel lobbies [32]. Further, it has been speculated that the use of different types of fancy yarn, including bouclé yarns, in the design of fashion and clothes is expected to expand [29]. This is because the search for decoration and novelty in fashion is an endless task [24].

2.3 Assessment of the Structure and Quality Parameters of Fancy Yarn and Multi-thread Bouclé Yarn

The structure and quality of bouclé and semi-bouclé yarns and the other types of multi-thread fancy yarn have been assessed using several methods. Examples of those methods are:

- the subjective assessment given by a panel of experts [38];
- the use of an Uster Tester [38, 45];

- the ratio of the maximum diameter to the nominal diameter of, mainly, fancy slub yarn, as suggested by Testore and Minero [25];
- the irregularity indices of knop yarn, as suggested by Testore and Guala [46];
- the 'shape coefficient of fancy yarn', which was suggested by Grabowska [43];
- the Constant Tension Transport Tester (CTTT), hairiness testers, travelling microscopes, the Digital Image Processing, and the Morphological Image Processing which were all used by Sudhakar [47]; etc.

The main advantage of those methods is that they give an indication for comparison between the fancy yarns. However, those methods are either limited to one type of fancy yarn or not sufficient by their own to account for the structure and quality of fancy yarns. Therefore, combinations of those methods were usually used [38, 47].

In an attempt to overcome the previous limitations, other methods of assessment of fancy yarns were detailed in previous studies by Alshukur [4, 28]. Alshukur's method benefits from the "quality parameters of fancy yarn"- including bouclé yarn. Those parameters are: the Size of Fancy Profile[6] (A), the Number of Fancy Profiles (N), the Circularity Ratio of Fancy Profile (CR), the Shape Factor of Fancy Yarn (ShF) and the Relative Shape Index of Fancy Yarn (RSI). Further details about those concepts, the approach of application, and the types of fancy yarn which can be assessed using those concept were given previously [4, 28]. Recently, those concepts were applied successfully to assess the quality and structure of gimp yarns and overfed fancy yarns [24, 37, 42].

2.4 The Structural Parameters of Multi-thread Fancy Yarn and Bouclé Yarn

The structural parameters of multi-thread fancy yarn, including bouclé yarn, are the parameters which help in determining and shaping the fancy yarn structure and are

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[6] Also known as the Area of Fancy Profile (A).

related to the structure itself. This is because the structure is also influenced by other parameters, such as the type of material of the fibres, the stiffness of the fibres, the stable length of fibres, the type of the input threads whether they are singles or twisted, etc. The structural parameters are set in accordance with each other to suit the type of fancy yarn that is intended to be made. Those parameters are:

- The number of the effect threads, which can be one [44], two [44] or in some rare cases can be three effect threads.
- The number of the core threads, which can be one or two threads [28, 29]. The total number of threads for the core, the effect and the binder together can be as high as six or more [32].
- The overfeed ratio of the effect thread(s). This ratio could be quoted as the nominal overfeed ratio (η%) showing the ratio between the supply speed (SS) and the delivery speed (DS) [24], that is:

$$\eta = \frac{SS}{DS} \times 100 \ \% \qquad (2.1)$$

  or could be quoted as the real overfeed ratio (Δ%) reflecting the difference between the speeds of delivery of the effect thread and the core thread [24, 25], that is:

$$\Delta = \frac{SS-DS}{DS} \times 100 \ \% \qquad (2.2)$$

  For example, the minimum, real overfeed ratio reported in a study was Δ%= 50% [48]; thus, the minimum, nominal overfeed ratio could have been reported as η%= 150% in the same study.

  The overfeed ratio may also be quoted as a theoretical ratio when it is measured by using the speeds of the driving rollers on the machine, i.e. SS and DS, or it can be quoted as an actual ratio if measured by using the actual lengths of the effect thread(s) yarns, L_e and the core thread, L_c . The term "overfeed ratio" used in this research refers to the nominal, theoretical overfeed ratio (η%). This ratio can also be reported as a simple ratio instead of a percentage ratio, that is:

$$\eta = \frac{SS}{DS} \qquad (2.3)$$

- The number of wraps of the binder, W, which is measured in wpm. The wraps can be reported as a theoretical value, that is:

$$W = \frac{RS}{DS} \tag{2.4}$$

  where RS is the rotational speed of the hollow spindle, or can be actual value if measured on the final fancy yarn. The theoretical number of wraps will be used in this research to mean “ the number of warps”.
- The thickness of the input threads. Usually, the effect thread(s) is thicker than the core thread. This in turn is thicker than the binder. The binder is usually a multi-filament [29], but it could also be a spun yarn [26, 40, 41, 48, 49].

2.5 The Structural Ratio of Multi-thread Fancy Yarn

2.5.1 Definition

The Structural Ratio of Multi-thread Fancy Yarn (SR) is a term that was introduced by the author of this thesis to help accounting for the structure of multi-thread fancy yarn-including bouclé yarn. It has the same equation as the Production Factor of Gimp Yarn (PF) which was given previously by the same author [24]. However, the name was changed to become the “Structural Ratio of Multi-thread Fancy Yarn” because it is a ratio between two parameters as shown below. The new name mimics the aspect ratio of textile fibres.

The Structural Ratio of Multi-thread Fancy Yarn is defined as the number of wraps of the binder (W) divided by the nominal overfeed ratio (η) of the effect thread [24]. This ratio is given by the equation:

$$SR = \frac{W}{\eta} \tag{2.5}$$

Therefore, this ratio is measured by wrap per metre (wpm). This ratio is useful when selecting the number of wraps that is needed to produce a specific type of multi-thread fancy yarn if the overfeed ratio is already given [24].

2.5.2 Utility of the Structural Ratio of Multi-thread Fancy Yarn

The Structural Ratio of Multi-thread Fancy Yarn accounts for both the overfeed ratio and the number of wraps which both have profound influences on the quality parameters of multi-thread fancy yarns. Extremely low or high values of those two structural parameters may result in a fancy yarn with a defective structure. Such a fancy yarn may prove to have poor saleability or, in some other circumstances, it may be considered useless [24].

Since the number of wraps and the overfeed ratio are interacting factors for multi-thread fancy yarn, any value chosen for one of them affects the value to be chosen for the other one [24]. The problem is that fancy yarn experts or textbooks do not usually provide specific values for those two structural parameters. Sometimes, only the minimum or maximum overfeed ratio is provided for a particular type of fancy yarn, as it was reported for loop yarns [29] and a variant of bouclé yarn [48]. Therefore, the Structural Ratio of Multi-thread Fancy Yarn helps to challenge such obstacles and to clarify the situation while making the fancy yarns [24].

2.6 Importance of Fibre Source and Properties on the Structure of Bouclé Yarns and Similar Fancy Yarns

Since the properties of fabrics are related to the properties of the constituent yarns, which in turn are related to the properties of the fibres [11], understanding the properties of fabrics made of fancy yarns requires an understanding of the properties of the constituent fancy yarns. This is gained by considering, amongst other factors, the fibres used to make the fancy yarns [29]. Moreover, reproducing a fancy yarn requires a careful laboratory analysis to the composition, length and fineness of the fibres used to make it [25]. This is because a minor change in the raw materials, or the processing conditions, may have a significant change to the style, structure and appearance of fancy yarn [38]. Therefore, it is important to the designers and the manufacturers of fancy yarn to be conversant and fully aware of the characteristics of the component materials of fancy yarns [24]. However, only two studies addressed the importance of fibre type and source as key factors to fancy yarn manufacture [39, 50].

In the first study, Mole and Knox studied the influence of the effect fibres on a particular variant of bouclé yarn, made of drafted fibres, which they called “terry-pile bouclé yarn”. This variant of bouclé yarn has profiles which, if knitted or woven, give an effect similar to the loop-pile effect obtained when regular terry fabrics are made [39]. Using medium- and long-length staple fibres in the range of 31 ~ 135 mm to make the effect profiles, it was reported that:

- Cotton fibres gave a bouclé yarn with pile appearance because of protruding fibre ends on the yarn surface.
- A blend of polyester fibres and cotton fibres gave springy protruding piles which might be explained by the bulk introduced to the effect component by polyester fibres.
- A blend of acrylic fibres and cotton fibres yielded soft and looped profiles in the fancy yarns. It was thought that the 135 mm long acrylic fibres caused the loop formation.
- A blend of viscose fibres and cotton fibres produced softer yarns than those made of cotton fibres and polyester fibres.
- When medium-length fibres were used, high drafting ratios created compact bouclé profiles [39].

Such a study showed that changes in the composition of the constituent fibres caused several types of changes to the resultant fancy profiles. Those changes were:

- Substantial changes related to the type or style of the resulting fancy profile, i.e., bouclé, terry-piles, loops, etc.
- Remarkable changes in terms of the appearance of the fancy profiles, i.e. hairy, compact, etc.
- Inherent changes pertain to those invisible qualities that may only be observed by handling the fancy yarn, i.e. being soft, springy, etc.

Building upon that, similar studies may be required to consider the case of fancy yarns having multi-thread structure. However, conducting such studies may be extremely difficult or not readily possible. The main difficulties are related to the number of parameters that should be fixed before spinning the input threads necessary to make multi-thread fancy yarns. Example of those parameters are the use of fibres equal in length and fineness, fixing the number of fibres in the input threads, using the same spinning conditions, the same spinning system and spinning machine, etc. Following that it is necessary to include a wide range of fibre types to obtain a reliable comparison. However, the main two problems here are the huge number of fibre types commercially available and the lack of a universal spinning system or spinning machine that are suitable for all types of fibres. Again, even when the same spinning system and machines were used for staple fibres, a huge number of multi-filament yarns will be excluded from such a study. For example, if polyester staple fibres were spun on the short-spinning system, multi-filament polyester yarns would be automatically excluded from the study, and so on. Therefore, measuring the properties of input threads to find relationships with the fancy yarn characteristics is by far a much more realistic, feasible and useful approach.

In another experiment intended to optimise terry-pile bouclé yarn, only the influence of cotton fibre source was investigated [39]. American cotton fibres, Egyptian cotton fibres and Indian cotton fibres were used to create the effect component. The cotton strands used were rovings (carded and combed) and slivers (carded and combed, and drafted once or twice). Fibre lengths ranged between 27~33 mm, while the content of short fibres was in the range 24.3 ~ 27.4%. The irregularity ratio (U%) of the cotton strands was in the range 9.5 ~ 15 %. The best results were reported for the American medium-length cotton fibres because the combed sliver (U=10%) prepared from them gave a fancy yarn resembling ribbons because it provided plenty of fibre ends on the effect component surface. However, the roving prepared from the American cotton (U=9.5%), whether carded or combed, gave rounded profiles that were suitable to make soft fabrics with ‘lofty’ effect. Further, differences in the style of the bouclé yarns made of slivers and those made of rovings were shown; the rovings gave bulkier terry-pile bouclé yarns. When those yarns were knitted or woven, the pile characteristics reported were different from the other yarns made of slivers [39].

It can be inferred from this study that the lower the irregularity ratio of the roving or the sliver, the better, or more favourable, are the characteristics of the resultant terry-pile bouclé profiles. Additionally, the medium-length cotton fibres were more appropriate to make such a variant of bouclé yarn. However, since the cotton fibres, the rovings or the slivers used were different in terms of fibre length, the irregularity ratio (*U*%) or the short fibre content, those results reported above were not fully explained in terms of actual parameters- except of the fibre source.

Since bouclé yarns and loop yarns belong to the same family of fancy yarn [3], it is useful to get an insight from loop yarns related to the same matter. An article discussing the loop profile formation concluded that the constituent fibres must be both long and stiff enough to ensure the loop profile formation and to impart the loop yarns a sufficient degree of lustre [50]. However, this study was only descriptive rather than being based on a rigorous scientific approach; perhaps it was an opinion article instead of a research article. Such a study may be more useful if the author took into account a wide range of fibre types, measured the bending stiffness of those fibres, selected a wide range of fibre bending stiffness and then used a wide range of fibre lengths. Following this, the technique of Design of Experiments (DOE) may be used to implement combinations of the factors suggested for the study. Further, the type of the spinning system used, and the stages of the manufacturing process must be detailed. It would also be more useful if a specific tool for measuring the loop profile lustre and the Circularity Ratio of Loop Profiles [4] were given for each combination of the previous factors. Therefore, it may be possible to build a table showing the fibre type, length and stiffness that are suitable to make loop profiles. Such a table, if given, may be indispensable for loop yarn manufacturers.

2.7 Influence of Properties of Input Yarns on the Structure of Multi-thread Bouclé Yarn and Similar Fancy Yarn

The contributions of several properties of input yarns to the structure and quality of multi-thread bouclé yarns, and similar fancy yarns, were revealed in several studies. For example, the diameters of the input threads were the main parameters in a study conducted by Petrulytė about overfed fancy yarns made on the hollow-spindle system [34]. The other factors of that study were the delivery speed of the products and the rotational speed of the hollow-spindle. Petrulytė wanted to predict the length of the binder of seven variants of fancy yarn which all have two effect threads, one core thread and a binder. The results of such a study showed that the deviation between the predicted values and the experimental values for 5 out of 7 variants of the fancy yarn were high and in the range of +13.1 ~ +14.7%. The deviations for the remaining two variants were low, i.e. 0.9% and -4.6% [34]. The problem of this study was that there was contradiction in the information given about the material used. The table of material showed that the core component was made of two or one threads, while the effect component was made of one thread. However, the opposite information were given in the text of the same article.

Following this, the linear densities and the overall densities of the input threads were some of the parameters considered in two studies aimed at predicting the coil length of the binder of fancy yarns made on hollow-spindle machines [33, 35]. The products studied in one of those two studies were covered yarns and overfed fancy yarns [35]. The remaining parameters of such a study were the delivery speed of the products, the rotational speed of the hollow-spindle, the twist of the fancy yarns and the stretch ratio (due to wrapping) of the core thread [35]. The experimental work showed that all the values predicted for the fancy yarns were greater than those resulted experimentally; the deviation was in the range +1.6 ~ +11.8%. For the covered yarns the deviation was in the range -15.2 ~ 6.0% [35]. Higher deviations were expected for the cover yarns since there were two covering components and they were superimposed above each other. Applying the covered components required the use of two hollow-spindles, so the variability created by the first covering stage was expected to be exaggerated by the second covering stage.

In the second study, the authors studied ten variants of overfed fancy yarns [33]. The additional parameters of that study were the delivery speed and the number of rotation on the hollow-spindle. The fancy yarns had either one or two core threads, one effect thread and a binder. The authors provided an equation to calculate the length of the binder. The deviation of the experimental results from the predicted values was less than 2% for 7 out of 10 variants, while it was in the range -6.4 ~ +5.7% for the remaining three variants [33].

Although the geometrical models of the previous three studies were tested on seven [34, 35] or ten [33] variants of fancy yarns, the authors did not provide a rigorous statistical analysis to their work. The size of the samples, the significance levels and the correlation coefficients between the predicted values and the experimental values were not provided. However, an advantage of those models is that they were built by following one approach. Moreover, one benefit of those models is that they accounted for the geometry and length of the binder which is an important component of the fancy yarn structure. Therefore, a similar study on the binder may be superfluous. A second benefit is that those studies were flexible because they gave the possibility to choose either the diameters of the components or their linear densities and volumetric densities in order to calculate the length of the binder.

In an attempt to increase the accuracy of their approach, Petrulytė and Petrulis, used 29 variants of multi-thread fancy yarn to compare the aforementioned theoretical models of the length of the binder [44]. Those variants of fancy yarns were made on a hollow-spindle machine and some of them had three components while others had four components [44]. The diameters and the number of input threads for the core component and the effect component were the parameters of such a study. A good agreement between the theoretical values and the experimental values was reported for 21 variants because the deviation of those did not exceed 5%. The author concluded that those three theoretical models were helpful for designing new types of overfed fancy yarn [44]. However, the ability of such models to help designing new types of fancy yarn can be doubted. This is because those models predict the length of the binder, whereas a new structure of the fancy yarn is related mainly to the geometry of the effect component and secondly to the geometry of the core component.

Two more comprehensive studies were conducted by Nergis and Candan who used input yarns that were different in various aspects, i.e. being singles or plied, coarse or fine, standard or high bulk [12, 13]. Those two studies also accounted for the influence of the wrapping direction of the binder, whether Z or S, on the bouclé yarn structure. The bouclé yarns of those studies were made in a one-stage process by a combined system. The main differences between the two studies were related to the type and thickness of the input threads, the types of knitting structure used to make fabrics from the resultant bouclé yarns and the further tests conducted on the fabric swatches. The results showed that the number of the effect profiles for the 100% overfed s-wrapped yarns was higher than those made at a 200% overfeed ratio. However, when the Z-wrapping was used, opposite results were reported. Further, following the use of coarser input threads, a significant increase in the average number of the profiles was reported. Moreover, the average height of the effect profiles was slightly greater for the Z-wrapped yarns than those of the S-wrapped yarns [12, 13]. The previous two studies gave consistent results regardless of the type and number of the input threads, which was an important aspect of them. They also showed that the structure of the resultant multi-thread bouclé yarn is more influenced by the manufacturing conditions than the type of material of the components. However, since the numerical results were not exactly the same, this suggests that the type, number and properties of the input threads may also be important to shape the structure of multi-thread bouclé yarn. This particular thought is important and can be built upon to start a new investigation.

More recently, a study was conducted on multi-thread gimp yarns made on the hollow-spindle system [42]. Such a study showed that using two singles threads, instead of one ply thread, in the core of the gimp yarns, gave positive benefits to the gimp yarn structure. Those benefits included reductions in the number, size and circularity ratio of non-gimp profiles. Moreover, a thicker 167/34 [7], textured polyester binder also decreased the number of non-gimp profiles and made them smaller than the case of a thinner, 145/77, regular nylon binder [42]. Since such a study showed the importance of the thickness of the binder to the structure of multi-thread fancy yarn, such as gimp yarns, bouclé yarns, etc., repetition in future studies should not be necessary.

2.8 Importance of Bending Stiffness of Input Threads for Making Fancy Yarn

The bending stiffness of the constituent yarns was thought to be important to define the shape of the effect profiles of fancy yarn [39, 42]. For example, it was observed that a thick, and stiff[8], core thread gave a strong base to support the effect profiles and made them protrude over the fancy yarn surface when making bouclé yarns and similar fancy yarns from drafted fibres [39]. The same study showed that when the bouclé profiles were lost due to undesirable settings of a hollow-spindle spinning machine, a thick core thread helped recovering some of those bouclé profiles and made them more identifiable [39]. In another study, the stiffness and types of the effect thread, the core thread and the binder were the parameters that were used to explain the results of a study on gimp yarns [42]. The gimp yarns were made on a hollow-spindle spinning machine in a one-stage process by combining several threads. The aim of such a study was to optimize the structure of the gimp yarns. This aim was achieved by studying non-gimp profiles, which may appear as defects on the gimp yarn structure. The approach of that study was based on using the technique of Design of Experiments[9] (DOE) [19]; the

[7] This term denotes for the linear density in decitex and the number of filaments, i.e. dtex/ filaments

[8] Although not specified explicitly in the original source, increasing the thickness of spun yarn without changing the type of material may result in similar increase to the bending stiffness of such a yarn.

[9] The DOE is a well-known statistical technique, but can be extremely complicated and difficult to understand if read from textbooks written for statistician. It is recommended, therefore, to read about it from a textbook that is written for engineers.

experimental design of that particular study had seven factors and two levels each. It was reported that a favourable gimp yarn structure may be achieved by choosing a material type for the effect thread that has sufficient bending stiffness. For example, using a relatively stiff bamboo ply yarn instead of a similar, but less stiff, cotton ply yarn created smaller non-gimp profiles, decreased their number and forced them to have less circularity ratio. These results were all advantageous to the gimp yarn structure [42]. Therefore, perhaps a similar study could be conducted on multi-thread bouclé yarns. However, instead of providing subjective judgement about the bending stiffness of the input threads, it would be more useful to find a method to measure such stiffness in numerical terms. So, a more rigorous approach would be followed.

Further, the variation of bending stiffness of the effect thread(s) of bouclé yarns may also be important because such variation may be reflected in a similar variation in the bouclé profile characteristics, i.e. size, number and circularity.

With regard to the measurements of yarn bending stiffness, the literature showed that initially there were the Quasi-Static Beam Method and the Ring-Loop Method[10] [51]. Both of these methods are manual and they usually measure the following components of yarn bending stiffness: the (elastic) bending stiffness, the coercive or frictional couple and bending recovery [52].

2.8.1 The Ring-Loop Method for Measuring the Bending Stiffness of Yarn

In the Ring-Loop Method a circular loop, or ring, has a radius ρ, made of the yarn being tested, is suspended by a pin and loaded by a suitable point load as shown in Figure 4 [23]. Due to the load *mg* (or *w*), it deforms by a distance *d* and changes shape to become similar to an ellipse. To estimate the bending stiffness (B) of yarn using the Ring-Loop Method, the following equation may be applicable [23]:

[10] Also known as the weighted-ring stiffness test for measuring yarn flexural rigidity [ibid].

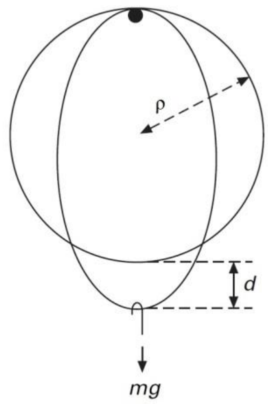

Figure 4 : Measurement of Bending Stiffness Using the Ring-Loop Method (reproduced from [23]**)**

$$\mathrm{B} = 0.0047\, w(2\pi\rho)^2 \frac{\cos\theta}{\tan\theta} \qquad (2.6)$$

Where:

$\theta = 493d/2\pi\,\rho$;

ρ is radius of the loop formed from the thread (mm);

2πρ is periphery of the loop, which is the length of each specimen before forming a loop of it (mm);

d is deflection of the lower end of the loop (mm); and

w is an applied point load (g).

This test was mainly designed for textile fibres [23], and following this it was used for yarns [52]. However, it was reported that errors may affect the accuracy of this test when the yarn being tested does not bend linearly [52]. Additionally, this method assumes that the distortion of the yarn loop under its own weight is negligible [52], where in reality it is not the case. It is possible to use this method in conjunction with other methods, though.

2.8.2 Using the Beam Method to Measure the Bending Stiffness of Yarn

It was shown that threads can be treated as beams when considering the problem of bending [51, 53, 54]; thus, the beam bending theory was applicable to measure the bending stiffness of threads [53]. The previous theory was investigated on yarns using two configurations of beam. These configuration were the cantilever beam [54] and a beam simply supported at one end while fixed at the other end (i.e. a built-in support) [53]. The equations used for each configuration was unique to that particular configuration and all derived from the beam bending theory.

Using a two-support beam system with small deflection angles, Ghane *el.al.* proposed a method to calculate the bending stiffness of yarns [53]. Each yarn was treated as an elastic beam supported by a simple support at one end while fixed at the other end by a piece of adhesive tape. 20 specimens of each yarn were tested over seven distances between the two supports, i.e. 30, 35, 40, 45, 50, 55 and 60 mm. The lengths of the specimens were 10% higher than each distance to prevent the yarns from falling down. A weight equal to 0.0041 g considered as a point load was placed on the yarns in the mid-distance between the supports (the jaws) in order to force the yarns to bend. Equations for the deflection of those yarns were presented and the deflection of a zero-twist PET multi-filament yarn was tested. The coordinates of the point of maximum deflection (X,Y) were considered in the calculations of bending stiffness of the yarns. The value of bending stiffness was, in this case, the slope of the regression model of those coordinates. It was shown that the relationship between the coordinates was linear when the maximum defection of the yarn $Y \leq 0.4$ cm. The correlation coefficient of that regression model was $r=0.842$ [53]. However, the significance of the regression model of that study was not reported, so, this study was statistically evaluated using the table of significance of regression models based on values of correlation coefficient and sample size [55]. The evaluation indicated that the regression model was significant at a significance level $\alpha=0.01$. Therefore, it was confirmed that beam configuration can be used to measure the bending stiffness of yarns. However, the procedures reported above may indicate a lack of accuracy, in particular due to the 10% extra length added to the specimens tested, and the location of the point load which may change when the yarn bends.

It is worth noting that there are three basic types for *statically determinate beams*, that is, the reactions at the supports can be obtained using the methods of statics. Those types of beams are the simply supported beam, the cantilever beam and the overhanging beam [9]. However, for *statically indeterminate beams*, combinations between several types of the supports and external forces may exist in a way which makes it not possible to obtain the reactions at the supports using the methods of statics. One of the typical types of *statically indeterminate beams* are beams supported using a two-support system. Several configurations may exist for this type of beam, and one of which is given in Figure 5 , that is, simply supported at one end and fixed at the other end [11].

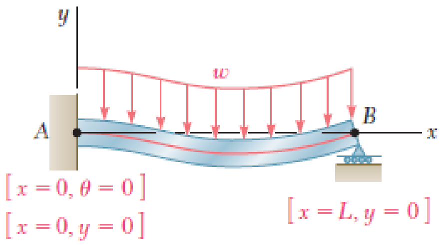

Figure 5: Deformed Beam *AB*

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[11] The ability of a beam to move, although there are supports, at its ends and the nature of the reactions of those supports are not the same; instead, they are related to the type of support. For a simple support, the beam end is allowed a free transverse movement so the reaction is only a force perpendicular to the surface on which the support freely moves. However, for a fixed support (or a built-in support) the beam end is restricted of movement in any direction and cannot rotate. Therefore, there is a reaction force having two components in the transverse and the perpendicular direction. Additionally, there is a couple (i.e. a moment).

Figure 5 shows a prismatic beam *AB* which was fixed at *A* and was supported by a simple support at *B*. The beam bent due to its own weight. The loading of this type of beam can be resolved into a bending moment and a shearing force [2]. Therefore, due to the shearing force, the bending moment varies from section to section for this type of beam. Consequently, the arc of curvature varies accordingly. This kind of bending is, therefore, not pure. The bending stiffness (denoted by B in this research, to match the terminology used in the manual of Kawabata's Pure Bending Tester KES-FB-2 [56], and also known as *EI* in mechanics) for this beam is given by the following equation [9]:

$$\mathrm{B} = \frac{w(-2x^4+5\mathrm{L}x^3-3L^2x^2)}{48\mathrm{L}y} \qquad (2.7)^{12}$$

Where: *L* is testing length of thread which should be the same as the distance between the jaws; *x*, *y* are the coordinates of the point of maximum deflection (*y* is always negative); and *w* is the total weight of the thread.

Equation (2.7) for calculating the bending stiffness of thread was simpler and easier to apply than those reported elsewhere [53]. Further, the bending stiffness of thread can be calculated readily from the equation without the need to use any regression model as reported previously [53]. Therefore, this configuration may be used to test the bending stiffness of yarn, although no work was reported on it.

More recently, using the cantilever beam configuration, Cornelissen and Akkerman analysed the bending behaviour of multi-filaments [54]. Four samples, ten specimens each, were tested. Sample lengths were 100, 125, 150 and 175 (±0.5 mm). It was reported that the bending behaviour of the threads was nonlinear, i.e. the displacement-curvature relationship was non-linear. Additionally, large deformations resulted and the cross-sections of the multi-filaments flattened, i.e. the strain-curvature relationship was also nonlinear. Further, it was shown that the contribution of shear rigidity to deflection was small in comparison to deflection due to bending stiffness. Furthermore, the results

[12] In theory, the deflection angle (φ) must be smaller than 6°, in order to apply equation (2.7).

of a multi-filament indicated that there were differences between the values expected theoretically and the values gathered experimentally. It was concluded that, when the cantilever configuration was considered, the theories of bending were not suitable to model the deflection of multi-filaments [54]. Therefore, since the cantilever configuration was not suitable, only the two-support beam configuration can be used to measure the bending stiffness of yarns.

2.8.3 The Use of Devices for Measuring the Bending Stiffness of Yarn

Since the phenomenon of yarn bending is complicated and has several components, new methods were suggested to measure and separate those different components of yarn bending stiffness. Those methods give quicker measurements and they benefit from the concept of pure bending [52], that is, when a yarn bends into a circular arc while shear forces are absent [2]. Two main devices were the pioneers of the new methods: the Shirley Cyclic Bending Tester, which was used previously [51], and the Kawabata's Pure Bending Tester KES-FB-2 [56]. It was also reported elsewhere that B. M. Chapman developed an apparatus for the same purpose in 1976 and it was called the automatic yarn-bending tester [6]. However, a common deficiency related to the aforementioned devices is that they were chiefly made to account for fabric bending stiffness rather than yarn bending stiffness. Further, when those devices are used to measure the bending stiffness of yarn, problems, deficiencies and disadvantages may arise. As observed, the problems related, for instance, to the Kawabata's Pure Bending Tester KES-FB-2 were:

- The manual of this device explains a method for testing a sheet of 20 (similar) segments of a yarn together [56], but in reality the various segments of the same yarn are different in many aspects, e.g. in thickness, shape, symmetry, packing density, the distribution of fibres, position of fibres within the yarn structure, size of fibre clusters, etc. [11]. This device, however, does not account for those differences.
- This device gives only the average value of the elastic bending stiffness but without the value of standard deviation [56]. This deficiency may not be as bad in a fabric form as it is in a yarn form. The reason for that is that in a fabric form, a group of

yarns bend together. Therefore, soft segments in one yarn may be compensated by stiff segments from adjacent yarns, and vice versa, in both the warp direction and the weft direction. Consequently, estimating only the average value of bending stiffness of a fabric may be acceptable within a specific tolerance. However, in a yarn form, doing so may not be acceptable because the yarn structure varies considerably along both its axis and its cross-section [11]. The variations in the yarn structure can be reflected in variations in the bending stiffness of the same yarn [11]. Not only is the bending stiffness important to the research of this thesis but also its variability, as mentioned in Section 2.8 above.

- The distance for measuring the (elastic) bending stiffness using this device is 1.1 cm [56]. An advantage of using a short distance for measuring such a property is that it may give the local, or point value of the stiffness. However, using a longer length of specimen may give the average value of stiffness over longer segments of yarn. In all cases, the distance used by the device is *extremely* short and cannot account for the impact of defects in the yarn structure, medium-term variation, long-term variation or many types of short-term variation in the linear density. Further, it is believed that the yarn structure defects normally have a profound impact on the value of bending stiffness. The Shirley Cyclic Bending Tester uses an even shorter length of yarn specimens (i.e. 0.5 cm) [52].
- The method shown in the manual of this device for the preparation of a sheet of 20 segment of a yarn [56] is concise. This method should have been explained in more details to prevent the subjective handling of the yarns by the person who uses the device.
- The 20 yarns forming the testing sheet should be tensioned exactly the same, but achieving that in reality may be extremely difficult.

It is believed that the other devices suffer from similar drawbacks. However, because those devices are more sensitive than the manual methods, researchers usually make use of both approaches [52]; thus, the results of both approaches can be compared with each other.

2.8.4 Variations in Spun-Yarn Structure and the Effect on its Bending Stiffness

Due to the inhomogeneity of textile fibres and the mechanical constraints of the processing machines, it is difficult to spin a regular yarn [57], that is, it is difficult to distribute fibre properties over the whole yarn, in all directions, in a uniform fashion [57]. Therefore, The yarn structure varies considerably, along both its axis and its cross-section (especially due to the phenomenon of fibre migration) [11]. Further, the successive segments of one fibre or filament are found to be periodically positioned within the yarn structure in various annular zones from surface to core to surface [11]. Added to that is the random grouping or clustering of fibres and the variation in twist or linear density of, particularly, (staple) spun yarns. Not to mention the differences in the packing density of (staple) spun yarn along its axis and cross-section [11]. All those factors lead in consequence to the creation of thin spots and thick spots along the yarn axis [11]. They also result in asymmetry and irregularity in the shape of yarns [11] (regardless of the spinning system used and type or length of the fibres). Further, in a poor-quality (staple) spun yarn, complex localised entanglements of fibres or hard spots, known as neps, may appear [11]. Moreover, due to the free ends of staple fibres, and because such fibres are processed in bulk as groups or subgroups, the free ends may protrude on the yarns surface, or they may hook, bend, buckle or roll on themselves in groups. Eventually, this may create a very complex yarn structure [11]. Furthermore, during multi-stage spinning processes, unevenness degree of fibre strand increases from stage to stage [57]. This is mainly due to drafting and the reduction in number of fibres forming the fibre strand [57]. Additionally, deficiencies in the drafting systems or the operations of the machines are extra sources of variation in yarn cross-sections [1]. Due to the previous factors, and according to Uster Statistics in 2007, only 50% of the short-staple spinning mills worldwide were able to spin 50 tex carded cotton yarns with a coefficient of variation of the mass less than 12.5% [58]. While spinning such yarns, only 5% of the spinning mills worldwide were able to reduce the number of thick places (+50%), thin places (-50%) and neps (+200%) per 1000 meters to approximately 40, 0 and 12 respectively [58].

The different spinning systems have their own unique sources of variation. For example, it is thought that a quasi-periodic variation may results in ring-spun yarns due to the formation of drafting wave in the fibre strands being drafted [59]. However, significant reductions to the irregularity of ring-spun yarns may be achieved by installing a compact spinning equipment on the ring spinning machine [60]. The irregularity in the mass (CV_m%) of rotor-spun yarns is better than their counterpart ring-spun yarns due to the phenomenon of back-doubling of the fibres in the rotor [1]. Rotor-spun yarns may have 60% and 80% lower number of thick places and neps, respectively, in comparison with ring-spun yarns [1]. Therefore, the irregularity limit (CV_{lim}) for rotor –spun yarns may be as 25% as lower than ring-spun yarns [1].

When spinning long fibres, comparison can be made between the worsted spinning system and the woollen spinning system. Worsted yarns usually have a more even structure than the woollen yarns; woollen yarns may have substantially uneven diameter and structure [11]. This is due to particularly the absence of drawing, combing and roving processes in the woollen system, which makes the production process short. Additionally, that part of the process following the card feed is such short that makes it difficult to correct any unevenness in the woollen yarns if made [61]. The other important factor creating substantial variation in the woollen yarn structure is introducing the condensers, which makes the slubbings or ropings. Those intermediate products have a particularly high tendency to be uneven [11, 61]. This is because the variation in the linear density of the many ends of roving made by the same condenser of a woollen card can be in the range of -6% ~ +7% of the mean value [11]. The pattern of this variation is also may vary from a woollen card to another [11]. It also may vary over time and when the tapes of the condenser, which divides the fibre web on the card condenser, are changed or maladjusted or tensioned wrongly [11].

To understand the relationship between the structure of a yarn and its bending stiffness, it is safe to say that the bending stiffness of a yarn is directly related to the number of fibres making that yarn [11], i.e. to its linear density. It is also related to the type of the structure. For example, air-jet spun yarns are recognised to have higher specific bending rigidity than an equivalent yarn spun using other spinning systems [59]. Ring-spun yarns are less rigid than similar rotor-spun or friction-spun yarns [59]. This is because of their larger diameters and the more compact cores [59]. Though, the helical arrangements of the fibres contribute to lowering the bending stiffness of ring-spun yarns [59]. It is also reported that woollen yarns are usually softer than similar worsted yarns [61].

All those aforementioned yarn structural variances may be reflected in the physical and performance characteristics of yarns [11], including their bending stiffness. Therefore, the CV% of bending stiffness of yarn may reach high values. For instance, it was demonstrated that the CV% of the deflection of a two ply cotton spun yarn (R96/2 tex) may be as high as 12.7% [52]. This value was reported when using the weighted-ring stiffness test to account for the non-linear bending behaviour of a yarn loop [52]. This study was the first to report an aspect of the variability of yarn bending stiffness. Though, this variability was reported indirectly, i.e. through quoting the CV% of deflection instead of the CV% of bending stiffness.

2.9 Parameters of the Hollow-spindle Machine that Affect the Structure and Geometry of Bouclé Yarn Made from Drafted Fibres

Baoyu and Oxenham studied the effect of production speed on bouclé yarns produced from slivers. The delivery speed was set between 25 and 125 m min^{-1}, at a fixed overfeed ratio equals to 180 %. It was found that when the production speed increased, the yarn count increased. However, the uniformity of bouclé yarns deteriorated, the height of the effect profiles decreased and the distance between them also decreased but with increasing variation. It was also found that the counts of the bouclé yarns correlated significantly with the distance between successive effect profiles. The appearance of the bouclé yarns was evaluated by taking into account the viewpoint of thirty experts. Those experts reported that when the production speed was raised, the effect profiles became more varied in size and more randomly distributed [38].

In another study on gimp yarns, loop yarns, bouclé yarns and variants of bouclé yarn called terry-pile bouclé yarns [39], made by drafting the effect fibres, the influences of fibre types, fibre strand type, delivery speed, supply speed and the drafting ratio were reported. Different fibre types (i.e. sliver or roving), slivers and rovings were used to make the fancy yarns on the Gemmill & Dunsmore #2 and #3 hollow-spindle spinning machines. In the first experiment, the researchers changed the delivery speed, the supply speed and the drafting ratio of the fibres. So, the fancy profiles and yarn structure changed accordingly. To make bouclé profiles using cotton fibres, it was necessary to run the machines at low delivery speeds and to use high overfeed ratio. However, increasing the delivery speed reduced the number of the bouclé profiles but created more gimp profiles. It was also found that a reduction in the drafting ratio made a fancy yarn with long profiles, but the actual bouclé shape was lost. Further reduction in both the delivery speed and the drafting ratio created a gimp yarn with intermittent, elongated wavy profiles. However, changing the core yarn to a thicker one helped recovering the bouclé profiles on the fancy yarns [39]. Although this experiment was important to the development work of the terry-pile bouclé yarns of their study, the researchers seemed to forget to supply the actual settings of the machines. They only reported the results but without the elaborated experimental data. Due to this deficiency, it is difficult to repeat their experimental work to validate it.

2.10 Parameters of the Hollow-spindle Machine that Affect the Structure of Multi-thread Fancy Yarns

The structure of multi-thread fancy yarn has previously been studied by accounting for the number of fancy profiles on the yarn surface, the length of the components within the fancy yarn structure, the shape of the cross-section of fancy yarn, the type of resultant fancy profiles, or the distance between the fancy profiles, etc. [14, 15, 18, 31]. These fancy yarn properties were found to relate mainly to three technological factors of hollow-spindle spinning machines. Those factors are:

- the delivery speed of the resultant fancy yarns,
- the supply speed of the effect component, and
- the rotational speed of the hollow-spindles [14, 15, 18, 31].

These three factors are inter-related and are set according to each other and the type of fancy yarn that is intended to be produced. The impact of combinations of these three factors over two or three levels each was studied using the technique of Design of Experiments [15, 18, 31, 42]. Using a fourteen-run experimental design[13], which had three levels for each of the delivery speed, the supply speed and the rotational speed, Ragaišienė and Petrulytė found that those three factors were significant in determining the number of the effect profiles. Those three factors also affected the ratio of the mass of the effect component to the mass of the whole fancy yarn; this ratio changed significantly in the range of 44.9 ~ 90.5 % when the combinations of levels of those factors changed [15]. However, this study did not separate the types of fancy profile from each other which makes it suitable to account for only overfed fancy yarns.

In another study [18], Petrulytė measured the impact of the delivery speed, the supply speed and the rotational speed on the formation of opened loops, closed loops, loop-knots, knots made from various loops, plain knots on generally overfed fancy yarns. This study was also based on a Box–Behnken response surface experimental design having fourteen combinations of the previous three factors, and three levels for each of them. It was found that increasing the supply speed made a significant increase to the number of plain knot-knot made from various loops, while the delivery speed had a negative contribution. Further, the relationship between the number of plain knot-knot made from various loops and the supply speed was positive, while it was negative with the delivery speed [18]. The importance of such a study to this research arises from the types of fancy profile studied. By looking at the photos of those types of fancy profile, and based on the criterion used in Section 1.1.2 of this thesis, it can be stated that the opened loops, loop-knots, and some of the closed, elongated loops were semi-bouclé profiles, while the knots made of various loops can be regarded as clusters of semi-bouclé profiles. Therefore, conducting a similar study will be avoided.

[13] Also known as a Box–Behnken response surface design.

Recently, Petrulytė investigated the impact of the supply speed, the delivery speed and the rotational speed on the formation of several types of periodical fancy profiles on overfed fancy yarn [31]. Those profiles were open loops, arcs, loop-knots, plain knots, snarls, long and extended knots made of dense coils. This study was also based on an experimental design having fourteen combinations of the previous three factors, and three levels for each of them. The results of this study showed that when the supply speed increased while the delivery speed decreased, the number of opened loop-arcs decreased intensively. This happened due to changes in nature of some of the resulting fancy profiles. Some of those profiles had profound changes in the dimensions longitudinally and transversally. Petrulytė presented a regression model for the number of opened loop-arc effects and reported a deviation of 6.6 ~ 26.2% between the theoretical values and the experimental results [31].

More recently, the influence of the false twist hooks attached to the outlet of the hollow spindles was investigated by Alshukur and Fotheringham [37]. It was concluded that those hooks should be always used even when the fancy yarn is made from threads rather than drafted fibres. The benefits of the false twist to the fancy yarns were regulating the structure of multi-thread fancy yarns and increasing its uniformity, increasing the number of fancy profiles and reducing the size of those profiles [37]. Following this, a more comprehensive study was reported by Alshukur and Fotheringham to optimize the structure of multi-thread gimp yarn [42]. This comprehensive study confirmed the benefits of false twist to the fancy yarn structure as reported previously [37]. However, it appeared to be relatively weak when compared with the influence of the core component, the effect component, the binder, the supply speed, the delivery speed and the rotational speed. The false twist hook was responsible only for approximately 2%, 5% and 7.5% of the total changes to the number of the defects on the gimp yarn structure, their area and their circularity ratio, respectively [42]. However, those ratios were thought to vary if different levels were selected for the factors of study.

It is thought that other factors of the hollow-spindle machines, such as tension of the components, may affect the formation of fancy yarns, but no studies have reported that.

2.11 Influences of the Direction and Number of Wraps on the Structure of Multi-thread Fancy Yarn

To account for the importance of wraps to the structure and geometry of fancy yarns made on hollow-spindle machines, several researchers studied combinations of the delivery speed and the rotational speed [14-18, 31]. Those studies were conducted at more than one level of the supply speed such that there would usually be three values for the overfeed ratio. To do so, the methodology used was mainly based on the Box-Behnken experimental design. A simpler approach, but without using the DOE, was followed in other studies [12, 13]. Generally speaking, the results of those studies were similar where increasing the number of wraps led to increases in the total number of profiles and reducing their dimensions or changing the type of the fancy profiles. However, it was found that when the materials used were changed, the effect of the wraps disappeared [15-17].

Ragaišienė and Petrulytė studied fancy yarns made using an elastomeric component covered with PA multi-filament in the core of their fancy yarns, two bulk multi-filament yarns in the effect of the fancy yarns and a PA multi-filament binder. It was found that the number of the effect loops and knots increased with the number of wraps [15]. Further, it was reported that changing the effect and the core of the fancy yarns to become 50 tex worsted threads did not bring about any significant change related to the number of the effect profiles. The authors, however, failed to put forward an explanation for these findings.

Following that study, Petrulytė reported that the number of opened loop-arc profiles on multi-thread fancy yarns increased when the number of the wraps increased [31]. Petrulytė attributed this result to the changes in the length of the effect component required to make the fancy effects. It was thought that when the number of wraps decreases, the pressure of the binder on the intermediate product, within the hollow-spindle, also decreased. Thus, it resulted in slacker wrappings while the unwrapped lengths of the intermediate product increased. The same author, however, did not find any relationships regarding the opened loop-loop/knot profiles or opened loop-plain knot profiles. [31]. In another study, Petrulytė failed to obtain, or present, clear relationships between the number of wraps and the number of plain knot-knot effects made from various loop profiles [18]. Petrulytė thought that the changes in the dimensions and character, i.e. type, of the effects were the reasons for the results of her study. However, perhaps the response surfaces used by her made the presentation of the results complicated. It would be better to use tables instead of those complicated figures. In recent study, it was reported that increasing the number of wraps, at fixed and low values of delivery speed, lead to a similar increase in the number of loop/knot and plain knot effect profiles. However, overwrapping the fancy yarn made a reduction to the number of those fancy profiles, even when the overfeed ratio was increased [14]. The author thought that the reason for this result was the changes in the length of the effect thread available for each fancy profile while being made.

Ragaišienė found that, at overfeed ratios η=1.5~1.6, when the number of wraps was increased from 280 to 500 wpm, open loops, closed loops, bosses and knots were formed. Further increases to the number of wraps to a maximum value of 666.7 wpm made more effect profiles. However, the height and the width of the effect profiles decreased, so smaller profiles were formed. Additionally, the distance between those profiles decreased [17]. It was claimed that those results were significant, which may confirm the importance of the number of wraps to the formation of multi-thread fancy yarns in general, though not specifically bouclé yarns. In another study, Ragaišienė used the same methodology but changed the materials and increased the number of fancy yarn properties studied to include the linear density of the fancy yarns [16]. However, the type of material was not included in the discussions as a factor that may influence the results. Such a study showed that, when the supply speed was 60 and 80 m min^{-1}, the number of the fancy profiles was positively related to the number of wraps. However, the width of the effect profiles was negatively related to the number of wraps when the rotational speed was 24000 rpm. In the previous two studies [16, 17], Ragaišienė used the same methodology and approach. She also made two groups of fancy yarn which differ from each other in terms of material type. The significant results obtained were limited to one group of the fancy yarns at a time. It can be inferred from those two studies that material type was an important factor in defining the structure of multi-thread fancy yarn. However, Ragaišienė did not attempt to discuss this assumption, nor did she attempt to include it in her explanations of the results obtained. She only presented the results and the value of coefficient of determination (R^2), and then she mentioned that some of the results were significant (as given above). However, she did not include the p-values or the significance level for each result claimed to be significant.

With regard to the combined system, it was found in two studies by Nergis and Candan that when the effect threads had S twist, and regardless of the overfed ratio used, the S-wrapped fancy yarns had more fancy profiles than the Z-wrapped fancy yarns [12, 13]. Although those two researchers used two overfeed ratios, i.e. 100 % and 200%, the number of profiles for the S-wrapped yarns was greater, than the case of overfeed ratio equalling 200%. However, opposite results were reported for the Z-wrapped bouclé yarns [12, 13]. Those two studies indicated that the Z-wrapping of the binder resulted in higher effect profiles than those made by the S-wrapping. However, the authors did not explain the reasons behind the results obtained.

2.12 Influence of the Overfeed Ratio on the Structure of Multi-thread Fancy Yarn

Several studies were conducted on the effect of the overfeed ratio on the structure of multi-thread fancy yarn [12, 15, 17, 18, 31]. Those studies showed that although increasing the overfeed ratio may increase the total number of fancy profiles on the fancy yarn, it may also affect the dimension [12] or type of the fancy profiles resulting [17]. Thus, it may increase the number of one particular type of fancy profile [18], at the expense of a reduction to the number of another type of profiles [31]. The authors of those studies claimed to obtain significant results, but they did not supply the significance levels of the results nor the p-values which may make it difficult to validate the conclusions of each study.

Ragaišienė and Petrulytė studied multi-thread fancy yarns produced on a hollow-spindle machine. It was found that the number of effect profiles, such as loops and knots, increased significantly with increasing the overfeed ratio [15]. However, the significance level was not given in this study. Moreover, a proportional relationship was found between the overfeed ratio and the number of plain knot-knot profiles made of various loops [18]. However, it was shown that the increase in the overfeed ratio made a reduction to the number of opened loop-arc profiles [31]. In another study, it was found that, regardless of direction of wraps or the number of wraps, the height of the bouclé profiles became significantly higher when the overfeed ratio was increased from 100 % to 200% [12]. The authors of that study did not show the significance level of their results, though.

Recently, Ragaišienė found that by increasing the overfeed ratio, the height and the width of the effect profiles and the number of effect profiles per unit length of the fancy yarns increased, whilst the distance between those profiles decreased. Additionally, the overfeed ratio had an impact on the type of fancy profile resulting [17]. The author claimed to use two combinations of the machine settings where the supply speed was 40 m min^{-1} and the delivery speed was 50 m min^{-1} without breaking the effect or the core yarns. These two combinations are “awkward” and they make negative overfeeding to the effect thread in comparison with the core thread, i.e. the overfeed ratio was 0.8, which is a serious problem to her research. However, Ragaišienė repeated her research but used different materials and increased the number of fancy yarn properties studied to include the linear density of the fancy yarns [16]. The results were similar to the previous research [17] and the overfeed ratio also had a positive relationship with the linear density of the fancy yarn. Further, increasing the overfeed ratio changed the type of the resultant fancy profiles (spirals, arcs, open and closed loops) [16]. However, this research was also based on two “awkward” combinations of the supply speed and the delivery speed that make negative overfeeding for the effect thread. Such negative overfeeding means a fundamental problem to the nature of fancy yarn where the effect is usually created by overfeeding the effect component in comparison with the core component, not the opposite. Therefore, it casts doubted on the results.

In another study, increasing the overfeed ratio, at fixed and low value of the delivery speed, lead to a similar increase in the number of loop/knot and plain knot effect profiles. However, further increases to the overfeed ratio did not increase the number of those profiles due to alterations to the type of the fancy profiles [14]. The reason for this was changes in the length of the effect thread that is available to create the fancy profiles on the intermediate product within the hollow spindle. Such a study showed that there were maximum limits to the overfeed ratio where exceeding it did not help improving the fancy yarn structure; instead, it started changing the type of fancy profiles.

2.13 Previous Attempts to Model the Structure of Bouclé Yarn and Other Fancy Yarns

Several researchers attempted to model the structures of several types of fancy yarn and multi-thread fancy yarn. The explicit and embedded aims of such studies were:

- to ensure the reproducibility of the fancy yarns without resorting to the experience of workers, empirical methods or the right/wrong trials [25];
- to provide a better understanding of the fancy yarn structures and the related manufacturing processes [15, 18, 31]; and
- to help in estimating the usage of raw materials or input yarns necessary to bring about a specific fancy yarn structure [35].

The modelling approaches used varied, over time and depending on the researchers, from pure mathematics and trigonometry to statistics (i.e. regression models), graphical (visual) models and "standard charts". The following sections show details of these approaches.

2.13.1 Mathematical Modelling

The first model of this kind was reported by Marton who modelled fancy yarns made by twisting together several threads [62]. Marton calculated the amount of twist remaining in the core thread, after being bound with the effect thread, using the following equation:

$$t_G = t'_G - t_E = t'_G - \frac{n}{V_E} \tag{2.8}$$

Where: *n* is the rotational speed of the spindle, t_E is the twist given to the twisted (fancy) yarn, t_G is the twist of the basic threads in the twisted (fancy) yarn, t'_G is the twist of the basic threads delivered to the pair of delivery rolls, and V_E is the speed of the twisted fancy roving[14].

Following this, an equation was introduced to calculate the overfeed ratio, *i*, depending on length L_z of one effect profile as follows:

$$i = \sqrt{1 + \frac{\pi^2 (d_G + d_Z)^2}{h^2}} \tag{2.9}$$

Where: *h* is the pitch height of a triangle made of the effect thread and the core thread by unravelling one coil of the fancy profile, d_G is diameter of the ground thread (i.e. the core thread), and d_Z is diameter of the effect thread.

When the fancy yarn has *m* coil layers, Marton presented the following equation to calculate the coil length L_Z:

$$L_Z = \pi\, m (d_G + \frac{m+1}{2} d_Z) \tag{2.10}$$

For knop yarns, and due to practical reasons, the *m* layers of coil may be distributed longitudinally over f number of adjacent coils; thus, the equation became:

$$L_{ZK} = \frac{\pi\, m}{\mathrm{f}} (d_G + \frac{\frac{m}{\mathrm{f}}+1}{2} d_Z) \tag{2.11}$$

Where L_{zk} is the length of the effect thread on a knop yarn having *m* layer of coils and distributed over f coil in the direction of the thread axis.

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[14] Sic - it should be the twisted fancy yarn instead of roving

This researcher attempted to generalise his equations by relating them to some types of fancy yarn, such as bouclé, nub, knot, loop, flamé and spiral fancy yarns. Although Marton called it bouclé, the technology and the manufacturing process described in his research are suitable to make gimp yarns rather than bouclé yarns. Perhaps the distinction between fancy yarn types was not always clear or agreed, in particular the structure of wavy yarn or gimp yarn with that of bouclé yarn. In terms of the mathematical rigour, the equations and the discussions related to them, as presented in Marton' article, have their own logic; however, Marton did not present any practical results to test the accuracy of his equations.

In another article, a model was presented by Testore and Minero to estimate the linear density of bouclé yarn regardless of its manufacturing process [25]. This model was also an attempt to account for the changes in the twist of the components due to the additional twisting (i.e. combining) twist which is used to make the bouclé yarns. Their equation was:

$$\left(1/_{T_0}\right) = \left(1/_{nT_e}\right) + \left(1/_{T_a}\right) + \left(1/_{T_r}\right) \tag{2.12}$$

Where: T_o is the final count of the boucle yarn, T_e is the count of the effect thread, T_a is the count of the core thread, T_r is the count of the binding thread and *n* is a coefficient which depends on the overfeed ratio of the effect thread.

Equation 2.12 is similar to the equation of calculating the (indirect) count of a regular ply yarn from the (indirect) counts of its components. The only new modification was the inclusion of the parameter *n*. Testore and Minero tested equation 2.12 and they presented charts to show the results. However, the sample size and the significance of the results were not provided which may make it difficult to repeat this research to validate its results.

Building upon the previous study, Testore and Guala conducted research on knop yarns and soufflé yarns [46]. The linear density of the soufflé yarn T_f was given by the following equation:

$$T_{\mathrm{f}} = \frac{(T_a \pm \Delta T_a)\left({W_a}/{W_s}\right)}{\left({W_a}/{W_s}\right) + (T_a \pm \Delta T_a) Q_m} \tag{2.13}$$

Where: Q_m is the weight of the roving at the output of the drawframe used, W_a/W_s is the ratio of input speeds of the core thread to the roving, T_a is the metric count of the core thread, while ΔT_a refers to the variations in the count of the core thread due to the new twist.

For knop yarns, irregularity indices for the yarn diameter and count were presented as percentage ratios, while the main equations were:

$$\left({1}/{T_{\mathrm{f}}}\right) = \left({1}/{T_o}\right) + \left({1}/{T_{knop}}\right) \tag{2.14}$$

$$B_i = \frac{T_{knop}}{T_o} \times 100 \tag{2.15}$$

Where: T_f is the count of the final fancy yarn, T_o is the count of the basic yarn, T_{knop} is the count of the yarn segments which have knops, B_i is the knopping coefficient which expresses the variations in the final knop yarn diameter because of the knops.

However, models 2.13, 2.14 and 2.15 were mainly related to the linear density and the variation in the linear density; thus, they account for a few aspects of the structure and the fancy yarn geometry. In all cases, understanding these aspects of the fancy yarn geometry is important before conducting more advanced studies. In the study of Testore and Guala [46], the experimental work was conducted on 15 trials. Three levels were selected for the total draft ratio, i.e. 36.5, 48.3 and 71.4. Three levels were also selected for the metric count of the roving (Ts), i.e. 0.2, 0.15 and 0.1 g m^{-1}. Two groups of soufflé yarns were made using two lots of acrylic fibres. It was found that using low values of the weight of the roving (Q_m) at the output of the drawframe, but with high ratio of input speeds of the core thread to the roving (W_a/W_s), the fancy yarns made were unified and course. Increasing the weight of the roving (Q_m) at the output of the drawframe, but with reducing the ratio of input speeds of the core thread to the roving (W_a/W_s), made quick increases to the count and the bulk of the fancy yarns.

In another study, Petrulytė studied several variants of overfed fancy yarn, made on a hollow-spindle machine, by modelling the binder configuration within the fancy yarn structure [34]. It was assumed that the cross-sections of all components were circular, the binder did not contract and the binder was wound helically around the effect thread and the core thread. Trigonometry was used to calculate the length of the binder (l_{b1}) as follows:

$$l_{b1} = \sqrt{P^2 + ({}^{V_d}/_{n_s})^2} \quad (2.16)$$

Where P is the height of a triangle made by unwrapping one helical coil of the binder, V_d is the delivery speed of the output and n_s is the rotational speed of the hollow-spindle.

Petrulytė suggested an equation to calculate the parameter P depending on the diameters of the input threads but she did not present the algorithm used to build such an equation. The experimental analysis of her study showed that the deviation between the real results and the theoretical values was in the range -4.6 and +14.7 % [34].

Petrulytė and Petrulis repeated the research but using two effect threads; thus, the equations they suggested were different. They used the linear density instead of yarn diameter to calculate the coil length of the binder (l_{b1}) as follows:

$$l_{b1} = \sqrt{4\pi(\frac{T_c+T_{e1}+T_{e2}}{T_c\delta_c+T_{e1}\delta_{e1}+T_{e2}\delta_{e2}} + \sqrt{\frac{T_b}{\delta_b}})^2 + (\frac{V_d}{n_s})^2} \quad (2.17)$$

Where T_c, T_{e1}, T_{e2} and T_b are the linear densities of the core, the first effect thread, the second effect thread and the binder, respectively; δ_c , δ_{e1} , δ_{e2} and δ_b are the overall densities of the same components, respectively. Equation 2.17 was tested and the deviation obtained between the real values and the expected values was in the range -6.4 and +5.7 % [33], which was an improvement over the previous models.

Moreover, Petrulis and Petrulytė proposed a theoretical method to calculate the coil length of threads arranged helically in complex-structured yarns [35]. Examples of those yarns were the covering components of covered yarns or the binder in fancy yarns produced in a one-stage process on hollow-spindle machines. The equations proposed were:

$$l_{11} = \sqrt{4\pi(\frac{T_c}{\delta_c(1+\varepsilon_1)} + \sqrt{\frac{T_1}{\delta_1}})^2 + (\frac{V_d}{n_{s1}})^2} \tag{2.18}$$

$$l_{21} = \sqrt{4\pi(\frac{T_c}{\delta_c(1+\varepsilon_1)} + \sqrt{\frac{T_2}{\delta_2}} + 2k_{e1}\sqrt{\frac{T_1}{\delta_1}})^2 + (\frac{V_d}{n_{s2}})^2} \tag{2.19}$$

$$k_{e1} = \frac{2n_{s1}}{V_d}\sqrt{\frac{T_1}{\pi\delta_1}} \tag{2.20}$$

$$l_{b1} = \sqrt{\left[(\frac{4}{\pi}\sqrt[4]{\frac{T_eT_c}{\delta_e\delta_c}} + 2\sqrt{\pi}\left(\sqrt{\frac{T_e}{\delta_c}} + \sqrt{\frac{T_b}{\delta_b}}\right) - \frac{\sqrt{\pi}}{90^\circ}\left(\sqrt{\frac{T_e}{\delta_e}} - \sqrt{\frac{T_c}{\delta_c}}\right)\arctan(\frac{2\sqrt[4]{\frac{T_eT_c}{\delta_e\delta_c}}}{\sqrt{\frac{T_e}{\delta_e}} - \sqrt{\frac{T_c}{\delta_c}}})\right]^2 + (\frac{V_d}{n_s})^2} \tag{2.21}$$

Where: l_{b1} is the coil length of the binder yarn, l_{11} is the length of one helix of the first covering component making the covered yarn, l_{21} is the average coil length of the second covering thread, T_1 is the linear density of the first covering component, T_2 is the linear density of the second covering component, δ_1 is the overall density of the first covering component, δ_2 is the overall density of the second covering component, K_{e1} is the coefficient of evenness of the intermediate product, ε_1 is the stretching ratio of the core thread during wrapping, n_{s1} is the rotational speed of the first spindle, n_{s2} is the rotational speed of the second spindle, and V_d is the delivery speed of the whole covered yarn.

To test models 2.18, 2.19, 2.20 and 2.21, the authors used five variants of fancy yarn made at different machine settings and component characteristics. The deviation between the real values and theoretical values for the fancy yarns was between +1.6 and +11.8 %, while for the covered yarns the deviation was between -15.2 and +6.0 % [35]. Models 2.17 till 2.21 importantly account for the binder as a component of fancy yarn structure, including bouclé yarn structure. The models reported in [35] may be regarded as an advanced level of the models concerned with one component of fancy yarn, although they were complex and had many parameters and variables.

So far, the models discussed above did not account specifically for bouclé yarns. However the first attempt to model the structures of bouclé yarn, loop yarn and snarl yarn mathematically was conducted by Grabowska [43]. The cycloid formula was used to model the bouclé yarn structure as follows:

$$x + \sqrt{y(2a - y)} = a \arccos \frac{a-y}{a} \tag{2.22}$$

while the (prolate) trochoid formula was used to model the loop yarn structure as follows:

$$x = a(t - \lambda sint);\ \ y = a(1 - \lambda cost);\ \lambda a = C_1 M;\ \lambda > 0 \tag{2.23}$$

Where *x* and *y* are the coordinate of a point in a line representing each function, *a* is the number of the effect profiles.

The first problem of this study is that symbols *t* and C_1 were only shown in the Figures 3 and 4 of that article, but left unexplained in the text. Additionally, the meaning of symbol λ is unknown, and the figures of the same article do not show it. This may make it difficult to understand the meaning of formulae 2.22 and 2.23 without reading a special mathematical textbook. Further, this researcher called the loop yarn "*loop yarn with a bouclé effect*" and called gimp or bouclé yarn "*loop yarn with sinusoidal effect*". Furthermore, it is understood that the equations of this research were used to describe the location of a point on the effect thread within the fancy yarn structure rather than to account for the structural parameters of multi-thread fancy yarn. The reason for this was the nature of Grabowska's research; she aimed at modelling the strength of such fancy yarns, therefore, her formulae followed a method suitable to achieve such an aim. Build up on that, Grabowska was only interested in testing the other models that accounted for the strength of those types of fancy yarn, while models 2.22 and 2.23 were left untested. This may make her research similar in nature to Marton's research, who left his equations untested [62].

2.13.2 Modelling Using "Standard Charts"

The usage of "standard charts" to model and predict the structure or to estimate the linear density of bouclé yarn and some other types of fancy yarn was first introduced by Testore and Minero [25]. Each standard chart proposed was based on simple mathematical equation and a large number of trials. Testore and Minero [25] aimed at estimating the changes in the twist of the components due to the combining twist needed to make the bouclé yarns. One standard chart of this study showed that the metric count of the bouclé yarns increases by increasing the overfeed ratio or the metric count of the effect thread, as given in equation 2.12 in the previous section. Another chart showed that, over three values of the overfeed ratio, the final twist given to the core and effect threads (before binding) increased with the metric count of the effect thread [25]. It is understood that the utility of those standard charts emerges from the fact they may give an insight about the trends of change to the parameters studied. However, the authors did not give the number of trials nor did they provide the significance of their results.

Following the previous study, Testore and Guala conducted a research on knop yarns and soufflé yarns [46]. Soufflé yarns are made by wrapping a roving around one or two threads, while knop yarns are made by inserting large fibre nubs into the woollen or worsted yarns. The diameter of the nub may be two to five times greater than the diameter of the basic thread. The charts of this article were built by including at least three parameters to show relationships between the ratio of the input speeds of the core thread to the roving (W_a/W_s), the metric count of the core thread (T_a), the metric count of the roving (T_s), the weight of the roving at the output of the drawframe (Q_m), and the metric count of the final fancy soufflé yarn (T_f). However, it was difficult to understand the meaning of the lines and curves shown in the charts, which may affect the utility of those charts. In all cases, it is possible to rely on the mathematical equations of this article to forecast the value of metric count of the final soufflé yarns from the previous parameters. Those equations were 2.13 and 2.14 as presented in Section 2.13.1.

2.13.3 Graphical and Visual Modelling

The graphical modelling of the fancy yarn structure is important to help in visualising the structure before creating the fancy yarn itself. For this purpose, Araujo *et. al.* suggested to use the CAD/CAM software in the Windows environment to design fancy yarns on the Gemmill & Dunsmore #3 hollow-spindle machines [63]. It was reported that those systems may allow the designing and the modifying of the fancy yarn structure automatically and they may help in simulating the final yarn pattern graphically. However, the performance of the software used was described as being related to the machine capabilities [63]. It was found that the graphical model reported in this article was simple and restricted to fasciated fancy yarns, i.e. wrapped yarns. The accuracy and the resolution of the example provided in the article were low. This is because of the limited capabilities of the computers and the software used in 1998. However, nowadays, such capabilities are tens of folds higher than before, which may improve this approach. Although such a model may be helpful in an industrial environment, it may lack accuracy if the mathematical rigour is absent. This issue could be mitigated if the finite element method (FEM) was used in conjunction with the visual modelling to study other properties of fancy yarn, such as the strength, heat transfer, abrasion, etc. The FEM may be superfluous and more than needed if the properties of the fancy yarns were not studied after presenting the visual models, though.

In another study, Zhang *et al.* created computer graphical models to simulate the effect appearance of loop yarns, wavy yarns (gimp or bouclé), and chenille yarns [64]. To present their models, Zhang *et al.* utilised the theories of computer graphics and computer simulation technology and took into account the structural characteristics of those types of fancy yarn. It was claimed that their study simulated the structural effect of those fancy yarns and solved the key problems of graphical expression of the appearance of them [64]. Building upon that, this work could be further expanded to simulate the vast collection of fancy yarns.

More recently, Liu *et al.* used a visual approach to determine the structural parameters of slub yarns made on the ringframe machines. Their model benefits from a feedback loop which compares the data collected from an already available slub yarn to those being made on the machine. Therefore, it allows automatic adjustment to be made to the mechanism responsible for producing the slubs. The author admitted that this method had *slight* inaccuracy because the slub lengths became about 10 mm longer than the values sought, while the distances between the slubs were 10 mm shorter [65]. Although slub yarns belong to a category of fancy yarn different from that of bouclé yarns, the idea itself seems interesting. Perhaps a similar application on bouclé yarns worth investigating in the future.

2.13.4 Statistical Modelling Using Regression Models

The literature indicated that several researchers used statistical regression models to account for the structure of several types of fancy yarn made on the hollow-spindle system [15, 18, 31]. Details of those studies are shown below.

Ragaišienė and Petrulytė studied fancy yarns produced using worsted and elastomeric covered components. The aim of their study was to account for the structural properties of multi-thread fancy yarn; in particular the number of effect profiles and the ratio of the effect component in the final yarn. The resultant models included linear, quadratic and interaction terms of the machine parameters [15]. In another study, Petrulytė constructed a statistical model that expressed the relationship between the technological parameters of the hollow-spindle machines and the number of the plain knot-knot[15] effect profiles made of various loops. It was found that this model was informative at the probability level $\alpha=0.05$. Petrulytė thought it may be possible to use that model to predict the number of plain knot-knot effects if the fancy yarn was made using the same system. However, no significant results were reported for opened loop-plain knots [18]. In a similar research, Petrulytė found that the regression model which expressed the relationship between the same technological parameters and the number of open loop-arc effect profiles was informative. Therefore, Petrulytė concluded that the model may be used to predict the structure of fancy yarn in terms of forming open loop-arc effect

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[15] This type of profile may be regarded as a semi-bouclé profile as shown in Section 2.10.

profiles. However, the regression model of the number of opened loop-loop/knot, and the model for opened loop-plain knot were not informative [31]. However, the problem of those three studies [15, 18, 31] is that the researchers did not take into account the fancy yarn count, the fancy yarn types and tension in the components. Further, they did not implement all types of the final effect profiles in the discussion and analysis.

In another study, Ragaišienė also used the hollow-spindle system and the same approach. Two variants of overfed fancy yarn were produced with one effect thread, one binder and either a singles thread or plied thread for the core [16]. The regression models put forward in this research were to account for the height of the effect profiles of the first fancy yarn, the width of the effect profiles of the first fancy yarn, the linear density of both types of fancy yarn and the number of effect profiles in a unit length of both types fancy yarn [16]. Only 9 out of 60 terms of those regression models were not significant, as Ragaišienė reported [16]. Ragaišienė repeated the research using a different type of material for the core and the effect components to make only one variant of overfed fancy yarn [17]. The regression models of this study predicted the number of the fancy profiles, the height of the profiles, the width of the profiles, and the distant between them. In this study, only 4 out of 40 terms of regression models were not significant [17].

The problem of the previous two studies [16, 17], however, was that it was claimed that it was possible to use the core yarns at a supply speed equals to 40 m min^{-1} when the delivery speed was 50 m min^{-1} (i.e. overfeed ratio= 0.8) without breaking the core or the effect threads. Further, it was also possible, as Ragaišienė claimed, to produce fancy yarns in two similar “awkward” combinations using the same condition when the overfeed ratio =0.8. However, it is believed that this situation seems to be impractical unless a suitable type of stretch thread was used for the core thread of the fancy yarn. Even with doing that, the stretch yarn may shrink back to its original length, which may force the core thread to make the fancy profiles. In doing so, the core thread would be exceeding its normal role in supporting the structure of fancy yarn.

2.13.5 Accounting for the Fancy Yarn Structure without Modelling

The literature showed that it was possible to account for the various characteristics of the fancy yarn structure without using any modelling technique. For example, Sudhakar, in his Masters dissertation, made use of a few methods and techniques to account for the various characteristics, texture and properties of fancy yarn [47]. Those techniques were the Constant Tension Transport Tester (CTT), a hairiness tester, a travelling microscope, the Digital Image Processing and the Morphological Image Processing. In particular, Sudhakar used these last two techniques to study the structure of gimp yarns and slub yarns [47].

Further, Grabowska introduced a parameter which she called the "shape coefficient of fancy yarn" to describe the structure of several types of fancy yarn [48]. However, a study reported by Alshukur discussing the utility of this coefficient found several problems associated with using it [4, 28]. First, its value is not an indication of the type of fancy yarn. This is because this shape coefficient may have the same value for different types of fancy yarn if they have equal diameters for the helices of the core and equal diameters for the helices of the effect threads. Second, Grabowska' shape coefficient of fancy yarn does not take into account:

- the real shape and dimensions of the effect profiles;
- the shape of the loops whether open, closed or uneven;
- the linear density of the whole fancy yarn;
- the twist of the components whether it is low, moderate or lively twist, in particular when the level of twist of the effect thread is important to make a loop yarn and a snarl yarn;
- the case of a fancy yarn which has several fancy profiles at the same time;
- the case where there are knots or slubs made of fibres or knots made of several loops; and
- it also ignored the type and flexural stiffness of the components which may affect the shape of fancy profiles.

In an attempt to overcome some of these drawbacks, Alshukur in his Masters' degree suggested other methods and parameters to account for the structure, appearance and quality of several types of fancy yarn [4]. Alshukur's quality parameters of fancy yarn quantify the structure and quality of fancy yarn. Those quality parameters are the Size (or Area) of Fancy Profile, the Number of Fancy Profiles, the Circularity Ratio of Fancy Profile, the Shape Factor of Fancy Yarn and the Relative Shape Index of Fancy Yarn [4].

Alshukur believed that his methods and parameters can be applied to assess the structure and quality of loop yarns, bouclé yarns, button yarns, knop yarns, slub yarns, eccentric yarns, cloud yarns, stripe yarns, snarl yarns, tape yarns, gimp yarns, nepp yarns and all derivatives of such fancy yarns. It was also claimed that the applicability of his methods and parameters to the previous types of fancy yarn was not affected by the type and form of the material making the effect profiles, i.e. whether the fancy effects are made of threads or drafted fibres [4]. Alshukur used Digital Image Processing and applied his methods successfully on gimp yarns, bouclé yarns and overfed fancy yarns [28]. As claimed, high level of agreement was obtained between the numerical results and the subjective assessment of the previous types of fancy yarn. However, Alshukur only applied his methods to a limited number of types of fancy yarn made on only the hollow-spindle system. So, it would be more useful to see actual results related to the other types of fancy yarn made using the various methods of making of fancy yarn.

Chapter 3: Methodology

The methodologies of this research varied considerably to suit the variable nature of multi-thread bouclé and semi-bouclé yarns. The approaches used were:

- Mathematical modelling, using trigonometry and calculus, which was used to build the theoretical framework (of this research) that was fundamental to understand the structure of multi-thread bouclé yarn, semi-bouclé yarn and other similar fancy yarns.
- Quantitative approach, which was used to gather the data from the experiments. Those data were necessary to test the theoretical model of the structure and for the objective assessment of the structure and quality of the resulting bouclé, semi-bouclé and similar fancy yarns.
- Qualitative approach, which was used to account for the subjective assessment of the quality and the structure of the resulting bouclé, semi-bouclé and similar fancy yarns.

The methods used to complete this research were as follows:

- The multi-thread bouclé yarns and semi-bouclé yarns was made by means of overfeeding the effect thread and wrapping it with the core thread on a hollow-spindle spinning machine type Gemmill & Dunsmore #3 (UK).
- The Systematic Approach of sampling[16] [66] was used as the sampling method to select samples for the various tests applied.
- The Beam Method was used as the main testing method to estimate the bending stiffness of the input yarns. To apply this method, it was required to develop a suitable testing frame. That testing frame was used in conjunction with the digital image processing technique. The results of this method were compared with the

[16] Also known as the quasi-random sampling.

Ring-Loop method for estimating the bending stiffness of yarns and with the measurements of the Kawabata's Pure Bending Tester KES-FB-2. The accuracy and consistency of the testing frame used were tested using control charts.

- The objective method introduced by Alshukur [4] were used for the objective assessment of the structure and quality of the resulting bouclé and semi-bouclé yarns. This method is explained in Section 3.1.1 below.
- Where required, and due to the lack of a panel of several experts, the author used his expertise to assess the structure and quality of the resulting fancy yarns subjectively.
- The input yarns were always stored in standard atmospheric conditions to reduce the influence of moisture content and temperature.

3.1 Method Used for Assessment of Bouclé Yarns and Similar Fancy Yarns

The bouclé and semi-bouclé yarns were assessed in two methods as follows:

3.1.1 Quantitative and Objective Assessment

The method introduced by Alshukur [4] was used in this research for the quantitative and objective assessment of the bouclé yarns made. To apply such a method, a microscope having a magnifying power at least 4X was used. For the fancy profiles tested, a suitable transparent plate made from glass was used to fix the fancy profile underneath it so as to make the fancy profile lie in a plane if it is not already so. Following this, a digital photo was taken for each fancy profile fixed by a transparent plate. Further, digital image analysis software was used to draw an ultimate, fitted polygon around the projection of fancy profile when viewed from the top. The same digital image analysis software was used to measure the area and the circularity ratio of the photos taken for the fancy profiles.

Sampling was carried out according to procedures approved by ISO standards (ISO 6939:1988(en)). The systematic method of sampling was used to select a representative sample for the bouclé profiles and semi-bouclé profiles of the bouclé yarns. Further details about the sampling method are given in Section 3.2 . The three meters of bouclé yarn at the beginning of each package were discarded in order to avoid damaged sections or sections made at the start-up of the production machine. The specimens were wound off the package slowly, smoothly and with care in order to prevent un-wrapping the binder wraps, or making the bouclé yarns snarl on themselves. When counting the number of bouclé profiles, the specimens were fixed by an adhesive tape on a metal ruler without cutting the bouclé yarns or separating them from the packages. Doing this ensured that the yarns were always straight without affecting the number of wraps.

This objective method of assessing the quality parameters of fancy yarns, including bouclé yarns, measured:

- **The Number of Fancy Profiles (N)**

This is the number of the bouclé and semi-bouclé profiles in the unit length of the bouclé yarn, i.e. decimetre. Counting was restricted to only bouclé and semi-bouclé profiles without counting other profiles, such as waves or knots, which could exist if the structural parameters of fancy yarn are not correctly set. The unit of measurement was profile per dm, i.e. dm^{-1}.

- **The Size of Fancy Profile (or Area of Fancy Profile) (A)**

This is the area of an ultimate, fitted polygon drawn to match the circumference of the projection of a bouclé and semi-bouclé profiles when seen under a microscope. Drawing such a fitted polygon was conducted using the image analysis software "analySIS FIVE®". The same software gave measurements of the area of the profiles as an average value with a standard deviation. The unit of measurements chosen was mm^2.

- **The Shape Factor of Fancy Yarn (ShF)**

This parameter is a dimensional parameter and it is obtained by multiplying the average area of the profiles by the average number of the profiles in a unit length of fancy yarn. The unit of measurement was $mm^2\ dm^{-1}$. This parameter is useful to account for the visual effects of the fancy profiles without considering the total linear density or thickness of the fancy yarns. Such a visual effect may also be known as the Absolute Bulkiness of the Fancy Profiles (regardless of the linear density or original thickness of the fancy yarn). Higher values of the ShF may indicate larger visual effects of the whole fancy yarns.

- **The Relative Shape Index of Fancy Yarn (RSI)**

The parameter is also a dimensional parameter and it is obtained by dividing the Shape Factor of Fancy Yarn by the linear density of the same fancy yarn. So, it is measured in mm^2 dm^{-1} tex^{-1}. This parameter is useful to account for the visual effect of the whole fancy yarn taking into account its thickness or linear density. This kind of visual effect is called the Relative Fancy Bulkiness of the Fancy Yarn. High values of the RSI indicate high Relative Fancy Bulkiness of the Fancy Yarn. This parameter is useful to compare several fancy yarns having the same structure, i.e. the same type or name, but are different in linear density, e.g. to compare several bouclé yarns between each other. The bulkier of them would have a higher RSI value. This parameter was reported for the fancy yarns in a few experiments when there were useful results related to it.

- **Linear Density of Fancy Yarn (T_{tex})**

The linear density of bouclé yarn was measured depending on the procedures mentioned in the international standard BSI ISO 2060:1995 [67]. The bouclé yarns were first preconditioned then conditioned according to BSI ISO Standard 139:2005 [68]. Since the linear density of fancy yarn is usually more than 100 tex, the length of each specimen sampled from the bouclé yarns made was 10 m. The number of specimens was 3 and the weight of the specimens was measured using a digital scale (Oertling) with 0.0001 gram sensitivity. The specimens were sampled, according to the systematic method of sampling, using a manual winding reel (DOODBRAND & CO. LTD, England). The sampling pitch between the specimens was 2 m.

- **The Circularity Ratio of Fancy Profile (CR)**

This parameter gives a description of the circularity or roundness of the representative projection of the fancy profile when the latter was observed under a microscope. The circularity ratio was calculated for each bouclé profile depending on the central moments of the fitted polygon which was drawn to match the circumference of the representative projection of the profile when the latter was seen under a microscope. The image analysis software "analySIS FIVE®" was used to measure the circularity ratio of the profiles and it gave the average values and standard deviations of the circularity ratio of bouclé and semi-bouclé profiles. This parameter is given as a percentage ratio (%) without any unit, and it was reported only for the fancy yarns in a few experiments when there were useful results related to it.

The average and the standard deviation values of the previous quality parameters of fancy yarn indicated the quality of the structure of the bouclé yarns. Although the fancy yarn structures (including bouclé) are based on deliberate variability, excessive levels of variation may indicate inferior quality of fancy yarns. The levels of variation, in the area or the number of the profiles of bouclé yarn were important to judge the quality of the bouclé and semi-bouclé yarns. For the sake of this investigation and as a practical rule, when the CV% values for the Size of Fancy Profile or the Number of Fancy Profiles were more than 40%, the Shape Factor of Fancy Yarn and the Relative Shape Index of Fancy Yarn were not be used to assess the visual fancy bulkiness of that particular fancy yarn. The ShF and RSI may lose their utility and become useless when the variation in the fancy yarn structure is extremely high. The 40% limit was chosen in this research to suit the three main, expected sources of variation in the product. Those are the variation which exists, or is expected, in the characteristics of the raw materials (i.e. the input yarns), the variation in the manufacturing process and any other further random variation which may exist [69].

When it was necessary to count the number of wraps of the binder of the bouclé yarns, the actual number of wraps was counted in a decimetre or a metre using three samples.

3.1.2 Subjective and Qualitative Assessment

The subjective assessment of the bouclé and semi-bouclé yarns was used in some of the experiments as needed. The reason for using it was to complete the comparison process between the fancy yarns made which was started by the objective assessment of the fancy yarns. Notes were made on the visual appearance of the fancy and bouclé yarns and the viewpoint of an assessor of the fancy yarns made was recorded. It was not possible to consult more than one assessor. In all cases, this method was not the main method of comparison between the fancy yarns made, but it was used only as a secondary method for appraising the fancy yarns made.

3.2 Sampling Methods of the Bouclé Yarn and Fancy Yarns Made

The systematic approach of sampling [66] was always followed to select samples for the various tests conducted on the bouclé yarns and semi-bouclé yarns made. This approach is often applied when the size of the statistical "population" is already known. However, when the population is not known, such as the case of fancy yarn, it can also be applied as follows:

- decide the sample size, say 15 specimens or fancy profiles;
- decide the sampling pitch, i.e. sampling distance in the case of yarns, say 1 metre;
- choose the first specimen randomly, i.e. any bouclé profile in the yarn;
- the fancy profiles to be selected should be 1 metre apart from each other along the bouclé yarn axis, i.e. the second fancy profile to be selected is 1 metre apart from the first fancy profile that is already chosen, and the third profile is 1 metre apart from the second profile, and so forth for the other fancy profiles until the sample size is reach;

The number of bouclé and semi-bouclé profiles were counted in one decimetre of the bouclé yarns. The sample size was 15 or 16 while the sampling pitch was 2 m. To select one decimetre-long yarn segments along the bouclé and semi-bouclé yarns, a manual winding reel (DOODBRAND & CO. LTD, England) was used.

To account for the Size of Fancy Profile, one of two approaches was followed for each experiment. In the first approach, the sample size was 30, and the sampling distance was 20 cm. In the second approach, the sample size was 15 and the sampling distance was either 50 or 100 cm. This alteration in the sampling approach showed the flexibility of the systematic method of sampling, without affecting the accuracy of the results. This is because one approach was chosen for each material property in each experiment, and it was consistent for each experiment, while the results of the experiments were not compared to each other. To apply those approaches, a bouclé profile was selected randomly from each bouclé yarn, while the other profiles selected were spaced apart along each bouclé yarn by a distance equalling the sampling pitch, i.e. either 20, 50 or 100 cm depending on the experiment. Accounting for the Circularity Ratio of Fancy Profile, followed the same approach used for the Size of Fancy Profile because the measurement of these two fancy yarn properties were obtained at the same time using the image analysis software “analySIS FIVE®”.

3.3 Statistical Tools Used for the Analysis of the Data of this Research

The statistical analysis was conducted using Minitab® 17.1.0. The statistical tools and test which were used to complete this research were:

- Anderson-Darling’s Test [70] was used to check the normality of the data collected as necessary. The null hypothesis was that the data fit a normal distribution, while the alternative hypothesis was that the data do not fit a normal distribution. Any p-value of the test lower than the significance level α=0.10 meant that the null hypothesis was rejected while the alternative hypothesis may be true;
- Where necessary, the variances in comparable data related to the input threads and the various bouclé yarns were compared using the Levene’s Test [70]. The null hypothesis was that those variances were equal, while the alternative hypothesis was that those variances were not equal. The significance level of the test was α=0.10. Any p-value of this test lower than α=0.10 meant that the null hypothesis was rejected while the alternative hypothesis may be true;
- t-Test was conducted to test the differences in the mean values between two comparable, but not necessarily paired, groups of data. The null hypothesis was that

those mean values were equal, while the alternative hypothesis was that those mean values were not equal. The significance level of the test was $\alpha=0.10$. Any p-value of this test lower than $\alpha=0.10$ meant that the null hypothesis was rejected while the alternative hypothesis may be true;

- Two-Way ANOVA test (Analysis of Variance) was used to test the difference between the groups taking into account the effect of all factors and their binary interactions. Any p-value lower than the significance level $\alpha=0.10$ meant that there is at least one group of data that is different from the other group;
- The significance level of comparison for each test was selected to be $\alpha=0.10$. Selecting a lower value of α to make the statistical tests more strict was not appropriate because the structure of fancy yarn is already based on deliberate variability;
- Simple and quadratic regression analysis;
- $\overline{x}$-SD Control Chart was used to estimate the reliability of the Improved Testing Frame, that is, its accuracy and stability over time. This chart was used to check whether the process of estimating the bending stiffness of the input yarns, using the Improved Testing Frame, was statistically under control or not; and
- Where necessary, the mean values of the bouclé yarn properties or input yarns properties were represented with 95% confidence intervals;

3.4 Method Used for Testing the Geometrical Model of Multi-thread Fancy Yarn

Since the aim of the geometrical model was to estimate the length of the effect thread required to make a multi-thread fancy yarn having specific structure, 15 variants of fancy yarn were made using different values of the length of the effect thread. Further, different material types, machine settings and fancy yarn structural parameters were used to produce the fancy yarns as given in Table 1. The advantage of this procedure was to prove the versatility of the model regardless of material type or machine settings. The machine settings of yarn 6 were left unrecorded. The reason for doing that was to prove that that the model can be applied even though the actual settings of the machine and the yarn structural parameters are not available. Doing so was not a problem, and the justification came from the fact that the main equations of the model (as given in Section 4.5) did not include the overfeed ratio of fancy yarn. Further, number of wraps of yarn 6 was counted easily, so the missing information about it was not important.

Three 10 mm-long segments of each fancy yarn were selected using the systematic method of sampling. The specimens were conditioned and tested in standard atmospheric conditions. Following this, the dimensions and number of the sigmoidal sections and the bouclé profiles found on those segments were measured and counted. The measurements were conducted using the image analysis software “analySIS FIVE®”. A calibrated rule was used for conversion from pixel to millimetre. Those measurements were used in the equations of the geometrical model which are suitable to the hollow-spindle spinning machine. The results of that were the estimated theoretical values of the length of the effect threads. Those values were compared against the set values of the length of the effect thread. Subsequently, the correlation, and the significance of the correlation, between the theoretical values and the real values of the effect thread were calculated. Normally, if the correlation value is high and significant, it is concluded that the model tested can be used to estimate the value that it accounts for, i.e. the length of the effect thread that is required to make a multi-thread fancy yarn on the hollow-spindle spinning machines, even if the parameters of manufacture are not known.

It was also required to count the number of wraps in those segments of fancy yarn, and then unravel those segments to measure the length of the core thread. The theoretical lengths of the effect thread were divided by the lengths of the core thread to obtain the overfeed ratio.

Table 1: Properties of Input Materials and Hollow-spindle Machine Settings Needed to Test the Geometrical Model of Fancy Yarn

Fancy Yarn	Effect Threads	Core Threads	Binder	Delivery Speed m min^{-1}	Supply Speed m min^{-1}	Rotational Speed rpm	The Overfeed Ratio η%	Theoretical Number of Wraps wpm
1	Lambswool 120/2 tex	undyed ply cotton yarn (R144/2 tex)	Rotor spun cotton yarn 29.5 tex	30	45	4500	150	150
2	Lambswool, 83 tex	wool/angora/polyamide 67 tex (60%/20%/20%)	nylon multi-filament (14.5 /77 tex)	30	50	8000	166	266
3	Wool 118/2 tex	R72/2 tex spun wool (Teflon coated) thread		30	50	7000	166	233
4	Wool 67 tex	Cotton R72/3 tex		30	54	5700	180	190
5	Cotton, R72/3 tex	Bamboo Ne= 24s/3		30	51	6800	170	226.7
6	Wool R120/2 tex	Natural wool R195/2 tex		Not recorded. The number of wraps was readily counted and it was 32 wrap per decimetre.				
7	Acrylic R72/2 tex	Acrylic R72/2 tex		20	33	3500	165	175
8	Cotton/Bamboo (80/20) R55/2 tex	Combed cotton R72/2 tex		15	24	2800	160	186.7
9	Lambswool 83 tex	Cotton/Bamboo (80/20) R55/2 tex		14	24	2800	171	200
10	Bamboo Ne=24s/3	Cotton/Bamboo (80/20) R55/2 tex		28	48	5600	171	200
11	Wool 68 tex	Cotton/Bamboo (80/20) R55/2 tex		28	44	5600	157	200
12	Cotton R72/2 tex	Cotton/Bamboo (80/20) R55/2 tex		28	47	5700	168	203
13	wool/angora/polyamide 67 tex (60%/20%/20%)	Cotton/Bamboo (80/20) R55/2 tex		35	46	8200	131	234.3
14	Coated wool R72/2 tex	Cotton/Bamboo (80/20) R55/2 tex		35	40	7000	114	200
15	Wool 67 tex	Coated wool R72/2 tex		35	45	7000	129	200

3.5 Method Used for Reverse-engineering the Fancy Yarns Based on the Results of the Geometrical Model of Multi-thread Fancy Yarn

It was decided to use the results of the geometrical model to make copies of the fancy yarns 9, 12, 13, 14 and 15. This is because the original deviations from the predicted length of the effect thread (L_e) for those five fancy yarns were: -7.18 %, -15.97 %, -0.78%, 1.19 % and 2.14 % respectively as given Table 19 in Section 5.1. So, such a deviation was either small or moderate in comparison with yarns 7 or 11. The input materials of the remanufacturing process were the same input materials used to make the original fancy yarns. The length of the effect thread (L_e) predicted using the geometrical model, and given in Table 19 in Section 5.1, was used to make the copies of the fancy yarns. The number of wraps used was the Actual Number of Wraps which is measured in the laboratory and is given in Table 2. The geometrical model assumes that the core thread was straight within the fancy yarn structure (although in reality it is not the case). Therefore, the predicted overfeed ratio was obtained by dividing the predicted length of the effect thread (L_e) by the length of the fancy yarn in which L_e was measured, i.e. dividing it by 10 mm.

Since there are several technological factors which affect such a manufacturing process, it was decided to make copies of those fancy yarns at the same levels of delivery speed that were used to make the original fancy yarns. However, the levels of the rotational speed and the supply speed were estimated manually as given in Table 2. It is worth noting that the spinning geometry in the First Spinning Zone was not controlled while making the first copies of the fancy yarns 9, 12, 13, 14 and 15. The calculations used to make those copies of the five fancy yarns are given in Table 2. Due to capabilities of the Gemmill & Dunsmore hollow-spindle machine, some calculations were rounded to the closest speed that can be set on the machine.

Table 2: Predicted Technological Parameters Used to Make Copies of Multi-thread Fancy Yarns

Technological Factor	Fancy Yarn 9	Fancy Yarn 12	Fancy Yarn 13	Fancy Yarn 14	Fancy Yarn 15
Actual Number of Wraps, W_{actual} , wpm	210	200	250	200	215
Predicted Length of Effect Thread, L_e, mm	18.1	19.6	12.9	10.9	12.6
Predicted Overfeed ratio $\eta_{predicted}=L_e/10$	1.81	1.96	1.29	1.09	1.26
Delivery Speed Used to Make the Yarn, DS, m min^{-1}	14	28	35	35	35
Predicted Supply Speed, $SS_{predicted}$ =DS × $\eta_{predicted}$, m min^{-1}	25.34	54.88	45.16	38.15	44.1
Supply Speed used for the first copy, SS_{used}, m min^{-1}	25	55	45	38	44
Supply Speed used for the second copy, SS_{used}, m min^{-1}	25	Not made	46	39	Not made
Predicted Rotational Speed, $RS_{predicted}$=DS × W_{actual} , rpm	2940	5600	8750	7000	7525
Rotational Speed used, RS_{used} , rpm	2900	5600	8700	7000	7500

Based on the results of comparison, it was decided to make a second copy of fancy yarn 9 by controlling the First Spinning Zone, that is, by reducing the level of Tension of the core thread and by decreasing the width of the spinning triangle to its lowest possible value, i.e. 4.5 mm. This procedure was not required for yarns 12, 13 and 15.

3.6 Method for Observing and Counting the Number of the Helices in the First Spinning Zone of the Hollow-spindle Spinning Machine

The length of the core thread was approximated to the length of the First Spinning Zone, i.e. L_c=40 mm. The fancy yarns were made using the same hollow-spindle machine, the same hollow spindle, the same workforce and the same core and binder threads. The number of the helices of the effect component in the First Spinning was calculated on the machine while running. This number was confirmed using photos taken for the First Spinning Zone by a Fujifilm FinePix A170 digital camera. However, difficulties arose because it was difficult to count the number of helices formed when the rotational speed was more than 9000 rpm. Further, it was not possible to measure the real values of radius *r* of effect-thread helices (which, if available, could be used for comparison with the theoretical values of *r*). There were several constraints which prevented the measurement of the actual value of *r*. Those constraints were:

- the limited space available in the First Spinning Zone;
- the inability to fix a measuring apparatus on the machine;
- the theoretical model assumed a steady-state case, but in reality it was not because of the vibration observed;

Therefore, only observations about the helices were reported and then compared with the theoretical values. Perhaps using a high speed camera may have overcome such a difficulty. However, a high speed camera was not available to this research. The only thing possible was to report an approximation of the minimum number of helices possible to observe. Although, such a number was an approximation in a few cases, it was suitable for the sake of this investigation because it gave an idea about the nature of the problems being investigated.

After estimating the number of the effect-thread helices, it was compared with the Number of Fancy Profiles. Further, the theoretical values of radius *r* were compared with the Size of Fancy Profile. Furthermore, the impact of the overfeed ratio, the rotational speed, the thickness and stiffness of the effect thread on the number of helices was estimated. This approach was practical and gave indication of the accuracy of the theoretical model of the effect-thread helices. The materials and the machine settings of the experiments related to the First Spinning Zone are given in Sections 3.6.1, 3.6.2, 3.6.3, and 3.6.4 below.

3.6.1 Materials and Machine Settings Used to Test the Influence of the Overfeed Ratio on the First Spinning Zone

The materials used for this experiment were:

- The effect thread was a 2-ply wool thread; its resultant linear density was R120/2 tex.
- The core thread was a 2-ply natural wool thread (R195/2 tex); and
- The binder was a nylon multi-filament (14.5/77 tex).

The procedures of this test were described in Section 3.5. To ensure exhaustive results, the overfeed ratios used were in the range η=1.2~2.2. The overfeed ratio was the variable of this experiment and was increased incrementally with the supply speed. The machine settings of this experiment are given in Table 3.

Table 3: Machine Settings to Test the Influence of the Overfeed Ratio on the First Spinning Zone

Machine Settings Number	Rotational Speed RS=5000 rpm; Delivery Speed DS=30 m min^{-1}	
	SS: Supply Speed; m min^{-1}	η: Overfeed Ratio
1	36	1.2
2	39	1.3
3	42	1.4
4	45	1.5
5	48	1.6
6	51	1.7
7	54	1.8
8	57	1.9
9	60	2
10	63	2.1
11	66	2.2

3.6.2 Materials and Machine Settings Used to Test the Influence of the Rotational Speed on the First Spinning Zone when the Number of Wraps was Changed

This experiment was conducted using rotational speed in the range RS=1000~9000 rpm and a number of wraps in the range W=33.3~300 wpm. The supply speed (SS) was 50 m min^{-1} and the delivery speed (DS) was 30 m min^{-1}. The overfeed ratio was fixed at η=166% (i.e. η=1.66) while the number of wraps (W) was changed incrementally with the rotational speed (RS). So, the variable of this experiment was the number of wraps. The machine settings are given in Table 4, while the material used were as follows:

- the effect thread was a 2-ply (Glenshear) wool thread (R120/2 tex),
- the core thread was a 2-ply bleached wool thread (R120/2 tex), and

- the binder thread was a nylon multi-filament (14.5/77 tex).

Table 4: Machine Settings Used to Test the Influence of the Rotational Speed and the Number of Wraps on the First Spinning Zone

Machine Settings Number	Rotational Speed (rpm)	Number of Wraps (wpm)
1	1000	33.3
2	2000	66.6
3	3000	100
4	4000	133.3
5	5000	166.6
6	6000	200
7	7000	233.3
8	8000	266.6
9	9000	300

3.6.3 Materials and Machine Settings Used to Test the Influence of the Rotational Speed on the First Spinning Zone and the Bouclé Yarn Structure when the Overfeed Ratio and the Number of Wraps were Fixed

The materials used were:

- the core component was a 67 tex 20% angora/60% wool/20% polyamide thread;
- the effect component was a 83 tex lambswool thread; and
- the binder thread was a 14.5/77 tex nylon multi-filament.

This experiment was conducted by fixing both the number of wraps at W= 180 wpm and the overfeed ratio at η=1.65. This was possible to do by changing the supply speed and the delivery speed in accordance with the changes made to rotational speed of the hollow spindle. So, the main variable of this machine was the rotational speed. Five different settings of the hollow-spindle machine were used as given in Table 5. The

Tension of the core thread was not controlled by the tensioning rollers. Instead, the core thread was only controlled by the tensioning guides.

Table 5: Machine Settings to Test the Influence of Only the Rotational Speed on the First Spinning Zone

Machine Settings Number	Delivery Speed, m min^{-1}	Rotational Speed, rpm	Supply Speed, m min^{-1}
1	20	3600	33
2	30	5400	50
3	45	8100	75
4	60	10800	100
5	75	13500	125

The trials of this experiment were randomised to minimise the variability which may result from uncontrolled factors such as the variability of the machine or the effect of the atmospheric conditions. The randomised order was to make yarn 1, then yarn 5, yarn 3, yarn 2 and finally yarn 4. It was observed that the high levels of speeds caused breaks to the core thread. This happened because the core thread Tension was proportionally related to the level of delivery speed. So, it was high at high production speeds and caused the core thread to break.

3.6.4 Materials and Machine Settings Used to Test the Influence of the Rotational Speed, Thickness and Stiffness of the Effect Thread on the Structure of Bouclé Yarn

The supply speed was SS=50 m min^{-1} while the delivery speed was DS=30 m min^{-1}. Therefore, the overfeed ratio was $\eta=(50/30)\times100=166\%$. Since the delivery speed was fixed, the number of wraps changed according to the changes made to the rotational speed. In this experiment, two groups of fancy yarns were made and the material used for them were:

- The core thread was an R72/2 tex spun wool (Teflon coated) thread;
- The binder thread was a 14.5/77 tex nylon multi-filament;
- To make Group I of fancy yarns, the effect component used was an 83 tex lambswool thread. It had an average value of bending stiffness B=0.549 g mm^2 and a standard deviation SD= 0.229 g mm^2; while
- To make Group II of fancy yarns, the effect component was a 2-ply wool thread (R118/2 tex). Its bending rigidity was B=4.20 g mm^2 and SD=1.13 g mm^2.

The settings of the machine are given in Table 6. The number of the helices was counted based on observations of the First Spinning Zone when the machine was running without taking photos. This was because taking photos did not increase the accuracy of such a procedure.

Table 6: Machine Settings to Test the Influence of the Rotational Speed, Thickness and Stiffness of the Effect Thread on the Structure of Bouclé Yarn

<table>
<tr><th>Machine Settings Number</th><th>Rotational Speed
rpm</th><td rowspan="7">Delivery Speed
DS=30 m min^{-1},

Supply Speed
SS=50 m min^{-1}</td><th>Number of Wraps
wpm</th></tr>
<tr><td>1</td><td>3000</td><td>100</td></tr>
<tr><td>2</td><td>4000</td><td>133</td></tr>
<tr><td>3</td><td>5000</td><td>166</td></tr>
<tr><td>4</td><td>6000</td><td>200</td></tr>
<tr><td>5</td><td>7000</td><td>233</td></tr>
<tr><td>6</td><td>8000</td><td>266</td></tr>
</table>

3.7 Procedure of Using the Kawabata's Pure Bending Tester KES-FB-2

To use this device for the measurement of bending stiffness of the input yarns, it was required to prepare a sheet of 20 parallel segments of each thread and to test them together. The length of the segments being tested was 11 mm. Those 20 parallel thread segments were distributed over 20 mm width-wise. Since they were tested together, this device only gave the average value of those 20 threads, but without the standard deviation. To obtain a rough estimation of the variability of bending stiffness of each thread using this device, five sheets were prepared from each thread and then tested. Since the Kawabata's Bending Tester was not placed in standard atmospheric conditions, the thread sheets themselves were taken from standard atmospheric conditions and tested within 5 minutes successively to reduce the impact of changes of the threads temperature and humidity on the test results.

The thread sheets were prepared in accordance with the manual of this device which showed a simple method for the preparation of a sheet of 20 threads [56]. It was understood that those threads have to be placed parallel to each other, tensioned exactly the same, and should not be touching each other. However, in reality preparing such a sheet was difficult without affecting the structure of the yarns being tested. For instance, it was difficult to tension the yarns at the same level. Consequently, while conducting the test, the thread specimens which were tensioned more than the others were thought to contribute more than the rest to the resulting value of (elastic) bending stiffness. Further, because the Kawabata device is extremely sensitive any slight movement or walking around it may have affected the results. Therefore, it was ensured that there was no movement around this device while conducting the test. Further details about the drawback of using this device to test yarns for bending are given in Section 2.8.3. In all cases, this device was used in this research only for the sake of comparison with other methods.

3.8 Procedure of Using the Ring-Loop Method for Measuring the Bending Stiffness of Yarn

The theoretical background about this method was given in Section 2.8.1. A sample of 15 specimens taken from each input thread was tested. Each of those specimens was prepared as a ring (i.e. a circular loop). The two ends of each specimen were connected together using a small droplet of superglue. However, due to wicking, the threads absorbed the superglue droplets. Consequently, an artificially long, and relatively stiff, connecting segments were formed in each loop. To reduce the impact of those stiff segments on the results, the connecting segments were used as the hanging point of each loop. However, due to internal stresses, it was impossible to secure the circular shape of the loops. This in turn was thought to affect the accuracy of this method. Therefore, this method was only used for the sake of comparison with the other methods. So, when testing a sewing thread, 15 specimens were prepared as loops in which the specimens had varying lengths, i.e. 60, 65, 70, 75 and 80 mm, i.e. three specimens were used for each length.

The hanging point of the loop was placed on a thin pin fixed to the wall of a well-illuminated conditioned laboratory. Following this, a weight w equalling 0.0335 g was placed gently on the lower part of the loop using a clipper. Due to this weight, the loop deflected and deformed to become elliptical. The distance of deflection *d* was measured using a commercial rule, with a minimum gradation of 0.5 mm, with the help of a magnifying lens.

3.9 The Beam Method as a Main Method for Estimating the Bending Stiffness of the Input Yarns

Building upon the information given in Section 2.8.2, the Beam Method were chosen to test the input yarns for bending, where those yarns were configured as two-support beam systems, but without using a point load. In other words, the threads were considered as *statically indeterminate beams* and they were left to bend under their own weight as shown in Figure 6. The bending stiffness B of this beam was given in equation 2.7 in Section 2.8.2.

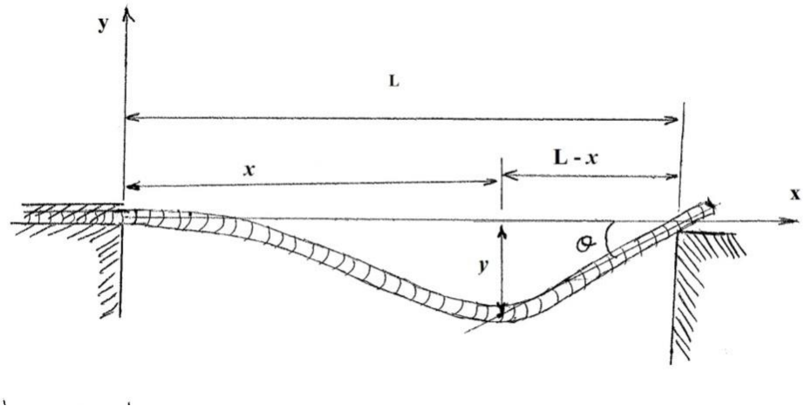

Figure 6: Schematic Diagram of Deflected Thread

The angle of deflection (φ) was approximated to the angle of maximum deflection (θ) which is shown in Figure 6. Angle (θ) was calculated by the equation:

$$\theta = \arctan\left(\frac{y}{L-x}\right) \tag{3.2}$$

Angles (θ) were accepted to be larger than (φ) because the variable nature of spun threads may make their bending behaviour not linear and not as smooth as the bending behaviour of statically indeterminate beams (shown in Figure 5 in Section 2.8.2). The attention and importance was given to the average value of angle θ when the measurements of B were normally distributed.

There are two approaches to measure the bending stiffness of thread: the fixed length test and the variable length test; the second approach was used in this research for two reasons:

- the threads were used mainly as the overfed effect threads and the overfeed ratio varies from experiment to another; and
- the bending stiffness of spun thread may be related to the test length because the structure of spun threads is not always uniform.

3.9.1 General Principle of Application

To apply the Beam Method, a suitable testing frame was needed. To create one, a development work was undertaken to make a testing frame with a suitable sensitivity, as shown in the following sections. The general principle of application of this method was as follow:

The threads were first preconditioned in an oven for 5 hours, then conditioned for a minimum of 48 hours in a standard atmosphere as stipulated in the BSI ISO Standard 139:2005 [68], i.e. the temperature were 20±2 C° and the relative humidity RH% was 65± 4%. Each of the threads was securely fixed at one end of the testing frames and simply supported at the other end, that is, left to lie on the second jaw of the bending frame free of any type of fastening (as shown in Figure 6). Such a thread was left to bend under its own weight for approximately two minutes; leaving the threads to bend for a longer time did not change the vertical distance of deflection *y*, and therefore, it did not alter the results. An exception to this rule was considered when the threads were thicker than 180 tex or stiffer than 10 g mm^2. Such a value was obtained based on an initial estimations and measurements. So, the threads which satisfy any of those two conditions were left to bend for at least three minutes. After finishing each test, the weight of each specimen was measured using a digital scale (Oertling) with 0.0001 gram sensitivity.

It was not possible to test all the input yarns at the same range of lengths. This is because the input yarns were different in thickness, material and type; thus, the ranges of testing lengths had to be suitable to the yarns being tested. So, another benefit of the aforementioned initial measurements was the ability to select a range of testing lengths for each input yarn. Further, it was expected of the input yarns to have different values of deflections for the different testing lengths (taken into consideration that the average value of the angle of maximum deflection (θ), was accepted). Further details about the lengths of yarns and method for calculating sample lengths are given in Appendix A. In all cases, both specimen length and weight was accounted for in equation 2.7 which was used for calculating the bending stiffness of the yarns as given in Section 2.8.2.

It was not possible to leave the free ends of the thread specimens on the free edge of the testing frame without causing the thread to fall down. The friction at the free ends of the thread specimens was not high enough to prevent the thread specimens from falling down. A solution was to increase the length of the thread specimens at the free end by 5 mm. The literature shows that other researchers used a similar approach by increasing the length of testing thread by 10% more than the distance between the jaws [53]. Such a procedure could deviate the results from the actual values. However, this procedure was consistent and applied for all samples. It was also justified by resorting to the results of the Anderson-Darling' Test [70] which was used to check if the bending stiffness values (B) were normally distributed. The bending stiffness values were expected to have a uniform distribution in the optimum situation, but a normal distribution in practice. Testing the normality of the results was not shown by other researchers elsewhere.

3.9.2 The Initial Bending Frame

An initial version of the bending frame used to estimate the bending stiffness of the input yarns is shown in Figure 7. This Initial Bending Frame consists of two plates which represent its two jaws. The distance between the jaws was set using a commercial ruler. The ruler is marked every half a millimetre. The co-ordinates of the point of maximum deflection were measured using two identical commercial rulers (as shown in Figure 7). One of them was put horizontally to measure *x* while the other was put vertically to measure *y*. Therefore, the maximum deflection of the input yarns was readily obtained from the rulers. The built-in support of this bending frame was created using a piece of adhesive tape. 15 specimens were used to measure the average value and standard deviation of bending stiffness of each input yarn. An estimate of the angle of maximum deflection (θ°) was conducted for each specimen using equation 3.2.

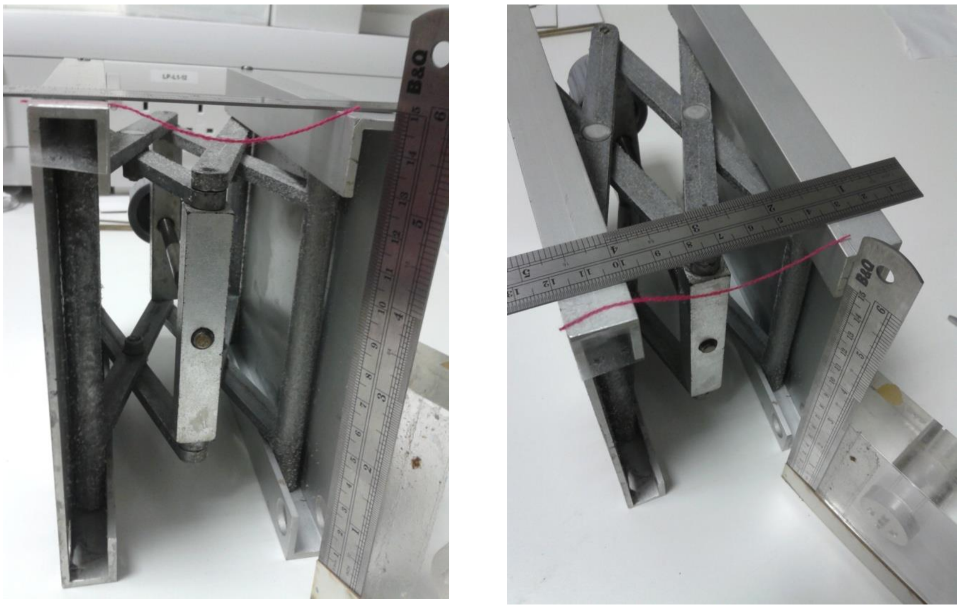

Figure 7: The Initial Bending Frame Used to Estimate Bending Stiffness of Threads

The data and full results of using this testing frame, including angles θ°, are given in Section A-1 of Appendix A. Those results showed that the variability in the measured values of bending stiffness of the threads was extremely high. So this bending frame was checked for accuracy and precision.

The accuracy of this bending frame was compared with the measurements of the Kawabata' Pure Bending Tester KES-FB-2 and the Ring-Loop Method. The precision of this frame was checked by testing a uniform material in two ways: by preparing specimens and test them more than once for the same specimen length or testing several specimens different in length. It was thought of testing a material having a low value of variability for bending stiffness. Such a material had to be similar in shape to threads. However, it should be isotropic, uniform and stable in dimensions and without internal stresses. Finding such a material was extremely difficult. So, trials were made using rubber strings and sewing threads.

When a rubber string was used, 11 tests were conducted using varying specimen lengths, i.e. 40, 45, 50 mm. Some specimens were tested once while others re-tested up to 4 times, to know if one specimen would give different values if tested several times. When a core-spun sewing thread, Ne=2/2/3 was used, the specimen length was fixed at 60 mm. Three specimens were tested three times successively in order to obtain the standard deviation of the individual results.

3.9.3 The Improved Bending Frame

Due to the low sensitivity of the Initial Bending Frame, an improved version of it was developed and called “the Improved Bending Frame”. The Initial Bending Frame was improved by fixing a sharp plate vertically on its left jaw so as to improve the nature of the simple support for the free ends of the threads being tested. Another plate was fixed horizontally on the top of the other jaw to maintain the horizontal level of the jaws. The nature of the built-in support was improved with the help of a peg. Further, the depth of deflection y as seen on the commercial rulers was read with the help of a magnifying lens. Figure 8 shows photos of this new version of the testing frame.

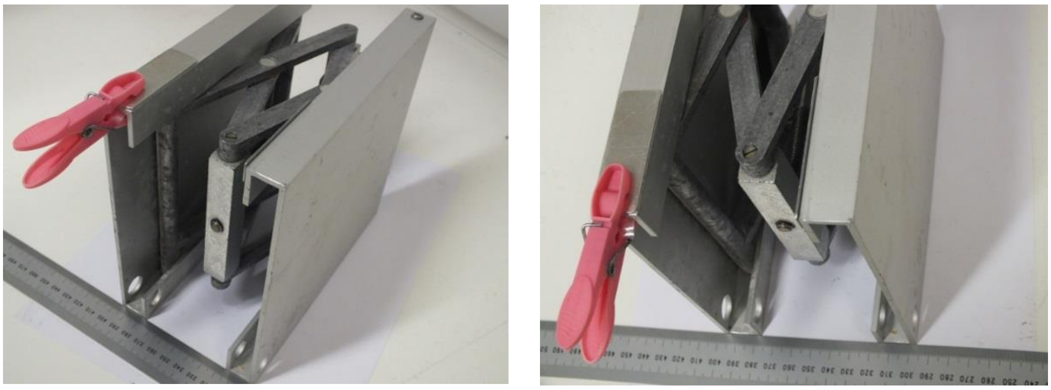

Figure 8: The Improved Bending Frame

3.9.4 Using the Digital Image Analysis and the Improved Bending Frame

A Fujifilm FinePix HS20 EXR camera was used to take images of the specimens after being bent, under their own weight, on the Improved Bending Frame. The image analysis software "analySIS FIVE®" was used to analyse the resulting images. The input yarn specimens were mounted on the Improved Bending Frame and were allowed to bend for approximately two minutes before taking the photos. Leaving the specimens for a longer time did not change the results. The camera mode while taking the shots was "EXR Auto Focus". The quality of the images was selected to be "Fine" to increase the number of pixels in the images. The distance of the camera base from the testing frame was approximately 11 cm. This distance was sufficient to allow the specimens to be mounted on the bending frame. Further, "Zooming-in" technique was used to allow the camera captures all the space between the jaws of the Improved Bending Frame. The test was conducted in a well-illuminated area of a conditioned laboratory that has standard atmospheric conditions. A calibrated ruler was used, in the photos taken, to allow conversion of unit of distance from pixel to mm. Because of the concave shape of the lens of the camera, the lengths of specimens measured by the image analysis technique was always different from the real length. Therefore, a Correction Factor (ε) was used to account for those differences where all measured lengths of specimen, *x* and *y* values were multiplied by (ε). This Correction Factor is given by the formula:

$$\varepsilon = L_{set}/L_{measured} \tag{3.3}$$

where L_{set} (mm) is the distance between the jaws as set by the assessor, and $L_{measured}$ is the measured value of the distance between the jaws, as they appear in the photos, after converting from pixel to mm.

3.9.5 Sample Preparation for Testing the Accuracy of the Improved Bending Frame When Using a Magnifying Lens to Read the Distances

Initially, a folded core-spun sewing thread, i.e. Ne= 2/2/3, was tested. 15 specimens were prepared and tested using a varying length of specimen, i.e. 50, 55, 60, 65 and 70 mm, i.e. three specimen for each length. However, due to permanent, internal, local stresses, high variation resulted. So paper strips and plastic strips were made and tested. Again, careful measures were taken while preparing specimens from those types of material to mitigate the impact of differences in the dimensions of the specimens on the measured values of bending stiffness.

4 mm-wide strips of paper (140 g mm^{-2}) were prepared from an A4-sized paper sheet. The strips were cut longitudinally using a laser cutter (FB Series Laser Cutter, CadCam Technology LTD, UK), to maximise uniformity, while they were cut width-wise manually by scissors. The length of the specimens was fixed at 110 mm. 20 specimens were tested.

Plastic strips were cut from a flat, A3-sized plastic sheet using a manual guillotine (rexel SmartCut A525pro). The 4 mm width of the specimens was set manually on this guillotine. 20 specimens were tested at constant test length equalling 110 mm. Furthermore, when measuring the impact of specimen length on the variability of bending stiffness, the lengths of the specimens were 90, 95, 100, 105 and 110 mm. Five specimens of each length were tested.

To test the precision, accuracy and the reproducibility of the Improved Bending Frame, the Statistical Process Control (SPC) technique was used. So, 100×4 mm plastic strips were prepared as mentioned above. To draw the $\overline{x}$-SD control chart for the testing process, the specimens were divided into subgroups of 5 specimens each. The specimens of each subgroup were tested successively but the subgroups were tested twice a day and over seven days. 70 specimens were tested in total and the data collected from the subgroups were used to draw an $\overline{x}$-SD control chart.

Since the specimens were cut manually on the guillotine, variation in the dimensions of the specimens was inevitable. To reduce the impact of this variation or the variation in the linear density on the results, the specific bending stiffness (measured in g mm^2 tex^{-2}) was used to plot the $\overline{x}$-SD control charts. Although this procedure is not ideal, it proved to be practical.

Although it is usually recommended to draw control charts using the data of 25 subgroups, fourteen subgroups were used to draw the $\overline{x}$-SD chart in this research in for the following reasons:

- Except for increasing or decreasing the distance between the jaws in order to set the length of the sample, the testing process does not include any moving parts before, after or during testing the threads. Therefore, the variability which may result may be related to the material or the person who does the test.
- The size of the subgroups (e.g. five specimens) met the requirements of control charts while the sample available was not enough to make more specimens.
- Further, the accuracy of the bending frame was tested using a variable length for the specimens. So, it was possible to assess the impact of changing the length of specimens on the variation in bending stiffness (if the yarn specimens to be tested using the Improved Bending Frame). If the mean value, standard deviation (or confidence intervals) were identical, similar to (or confounded with) the results of testing the specimens at a constant length, it would be concluded that the length of specimen would not have an impact on the values of bending stiffness (or it may only have a minor impact on the results). Therefore, the testing frame will be reliable in all cases.

3.10 Material and Machine Settings Used for Testing the Influence of Bending Stiffness of the Effect Threads on the Structure of Bouclé Yarns

Four bouclé yarns were made to assess the contribution of bending stiffness of the effect threads (B_e) to the structure and quality of bouclé yarns. Further, the results were confirmed by making two extra bouclé yarns. In all runs of this experiment, the same materials were used for the binder and the core component. However, the effect threads were changed from a run to another as shown in Table 7.

Table 7: Material Used to Test the Importance of Bending Stiffness of the Effect Thread and their Properties

Function of Input Yarn		Material Types	Colour[17]	Linear Density tex	Number of Input Yarns	Bending Stiffness B ($g\ mm^2$)	
						Average	**Standard Deviation**
Core component		Cotton/ lambswool	Undyed	R 120/2	1	3.662	1.774
Binder component		Nylon multi-filament	Light yellow	14.5/77	1	*	*
Effect component	Cone 1	Cotton	Amber	R 126/3	2	1.579	0.774
Effect component	Cone 2	Lambswool	Honeysuckle	R 120/2	2	2.518	0.966
Effect component	Cone 3	Natural wool	Undyed	R 195/2	2	5.249	1.601
Effect component	Cone 4	Stiff acrylic	Beige	140	2	18.3 (Estimated mathematically)	Not given
Effect component	Confirmation Cone 1	Wool/ polyamide	Aroma	R 120/2	2	3.183	1.671
Effect component	Confirmation Cone 2	Lambswool/ viscose	Gretna green	R 120/2	2	3.835	1.033

The delivery speed of the machine was DS=30 m min^{-1}, the supply speed was SS=60 m min^{-1} and the rotational speed was RS=6600 rpm. So, the number of wraps was W=RS/DS=6600/30 =220 wpm while the overfeed ratio was η=SS/DS =(60/30)×100=200 %.

[17] Colour is not important to all experiments. It was only mentioned for the sake of organising the work.

3.11 Material, Machine Settings and the Experimental Procedures Used for Testing the Influence of the Bending Stiffness of the Core thread on the Structure of Bouclé Yarn

The bouclé and semi-bouclé yarns were made using three input threads:

- The effect was a three-ply bamboo thread having a resultant linear density R74/3 tex (Ne= 24/3);
- The binder was a 14.5/77 tex nylon multi-filament; and
- The core was altered from a bouclé yarn to another as shown in Table 8.

The supply speed of the effect thread was SS=46 m min^{-1}. The rotational speed of the hollow-spindle was RS=6600 rpm. The delivery speed of the resultant bouclé yarns was DS=35 m min^{-1}. The overfeed ratio was η=SS/DS= (64/35) × 100 ≈183 %. The number of wraps W=RS/DS=6600/35≈188 wpm. The trials were randomised as shown in Table 8.

Table 8: Material Used to Test the Impact of Bending Stiffness of the Core Thread and Their Properties

Bouclé Yarn	Trial Order	Core Thread Material	Linear Density (tex)	Colour	Bending Stiffness (g mm^2)	SD of Bending Stiffness (g mm^2)
Yarn 1	1	lambswool	83	rose	0.549	0.229
Yarn 2	3	soft acrylic	R72/2	canary	0.650	0.154
Yarn 3	5	linen/cotton	R144/2	sand	2.029	0.872
Yarn 4	6	lambswool/viscose	R120/2	Gretna green	3.835	1.033
Yarn 5	4	natural wool	R195/2	natural	5.249	1.601
Yarn 6	2	wool/cotton	R163/2	snapdragon	8.636	4.324

3.12 Machine Settings and Material Used for Testing the Influence of the Overfeed Ratio on the Structure of Bouclé Yarn

Settings of the machine for this experiment are given in Table 9. The delivery speed and the rotational speed were fixed to keep a constant number of wraps W=200 wpm. To change the overfeed ratio (η%) incrementally, the supply speed of the effect threads was altered incrementally.

Table 9: Machine Settings and Yarn Structure When Testing the Effect of the Overfeed Ratio on the Structure of Bouclé Yarn

Machine Setting	Delivery Speed m min^{-1}	Supply Speed m min^{-1}	Rotational Speed rpm	Overfeed Ratio %	Number of Wraps wpm	Structural Ratio wpm	Resultant Bouclé Yarn
1	30	54	6000	180	200	1.11	yarn 1
2	30	60	6000	200	200	1	yarn 2
3	30	66	6000	220	200	090	yarn 3
4	30	72	6000	240	200	0.83	yarn 4
5	30	78	6000	260	200	0.77	yarn 5
6	30	63	6000	210	200	0.95	Confirmation yarn

The bouclé yarns of this experiment were made using the same number of wraps and four input threads:

- Two identical effect threads; each was a two-ply pure wool thread (quality: Glenshear) and the resultant linear density of each of them was R120/2 tex. The mean bending stiffness of each of the effect threads was 4.006 g mm^2 while the standard deviation was 1.116 g mm^2;
- The core thread was an undyed two-ply blended lambswool/cotton thread (R120/2 tex). The mean bending stiffness of the core thread was 3.662 g mm^2 and SD= 1.774 g mm^2; and

- The binder was a 14.5/77 tex nylon multi-filament.

3.13 Machine Settings and Material Used for Assessing the Influence of Number of Wraps on the Structure of Bouclé Yarn

The settings of the machine and the structural parameters of the resultant bouclé yarns are given in Table 10. The overfeed ratio (η%) remained constant for all the bouclé yarns. The number of wraps was increased incrementally by incremental increases to the rotational speed. The limitation of thicknesses of the components made it unpractical to use higher numbers of wraps.

Table 10: Machine Settings and Yarn Structure for Assessing the Influence of Number of Wraps on the Structure of Bouclé Yarn

Machine Setting	Delivery Speed m min^{-1}	Supply Speed m min^{-1}	Rotational Speed rpm	Number of Wraps (W) wpm	Overfeed Ratio η%	Structural Ratio (SR) wpm	Resultant Fancy Yarn
1	30	60	4800	160	200	0.80	yarn 1
2	30	60	5100	170		0.85	yarn 2
3	30	60	5400	180		0.90	yarn 3
4	30	60	5700	190		0.95	yarn 4
5	30	60	6000	200		1.00	yarn 5
6	30	60	6300	210		1.05	yarn 6
7	30	60	6600	220		1.10	yarn 7
8	30	60	6900	230	200	1.15	Confirmation yarn

The materials used to make all the bouclé yarns for this experiment were:

- The effect element of bouclé yarn was made using two identical threads; each was a two-ply blended wool/polyamide thread (R120/2 tex). Each had a mean value of bending stiffness was 3.183 g mm^2 and SD=1.671 g mm^2;

- The core component was an undyed two-ply blended lambswool/cotton thread (R120/2 tex). It had a mean value of bending stiffness B_c = 3.662 g mm^2 and SD=1.774 g mm^2; and
- The binder was a nylon multi-filament (R14.5/77 tex).

3.14 Material, Machine Settings and the Experimental Procedures Used for Mapping the Relationship between the Structural Parameters and the Quality Parameters of Bouclé Yarn

The material used to make the bouclé, semi-bouclé and overfed fancy yarns were:

- the binder was a nylon multi-filament (R14.5/77 tex);
- the core component was a (natural) 2-ply wool thread (R195/2 tex); and
- the effect threads were two identical threads and each of them was a 2-ply wool/nylon blended thread (R120/2 tex). The bending stiffness of the effect thread was B_e=2.963 g mm^2 and SD=1.212 g mm^2, so the CV% of B_e was 40.9 %.

The machine settings and the corresponding structural parameters of fancy yarn are given in Table 11.

Table 11: Machine Settings and Levels Selected for the Fancy Yarn Structural Parameters

Machine Settings			Structural Parameters		
DS: Delivery Speed (m min^{-1})	**SS: Supply Speed (m min^{-1})**	**RS: Rotational Speed (rpm)**	**η: the Overfeed Ratio (%)**	**W: Number of Wraps (wpm)**	**Number of the Effect Threads**
30	54	4800	180	160	2
	63	5700	210	190	
	75	6600	250	220	

This experiment was also based on a full factorial experimental design of nine trials (i.e. runs) as given in Table 12.

Table 12: The Experimental Design and Machine Settings to Map the Interaction Pattern between the Structural Parameters and Quality Parameters of Bouclé Yarn

Fancy Yarn	Randomised Order of Trials	Standard Order of Trials	RS: Rotational Speed (wpm)	SS: Supply Speed (m min^{-1})	DS: Delivery Speed (m min^{-1})	Number of Wraps (wpm)	The Overfeed Ratio (%)
Yarn 1	1	9	6600	75	30	220	250
Yarn 2	2	6	5700	75	30	190	250
Yarn 3	3	5	5700	63	30	190	210
Yarn 4	4	4	5700	54	30	190	180
Yarn 5	5	8	6600	63	30	220	210
Yarn 6	6	2	4800	63	30	160	210
Yarn 7	7	7	6600	54	30	220	180
Yarn 8	8	1	4800	54	30	160	180
Yarn 9	9	3	4800	75	30	160	250

The trials of this experiment were conducted randomly to minimise the influence of the machine variability or unstable levels of the factors on the results and the analysis. Due to the utility of the technique of the Design of Experiments, some of the trials would be useful to identify the machine settings or the structural parameters which were suitable to produce bouclé and semi-bouclé yarns and those useful to make other types of fancy yarn. It would also be possible to identify the trials which were not suitable to make any bouclé and semi-bouclé yarn, or any other type of fancy yarn at all.

The fancy yarns' characteristics were tested for normality (of the measurements) for the following reason: If the manufacturing process, raw materials (i.e. the input threads) and conditions of manufacturing were all optimum, it would be expected to obtain fancy yarns having perfect structures. This means that the fancy profiles would have the same area, circularity ratio and number per unit length of the ultimate fancy yarn. It also means that the same distance between successive fancy profiles would be equal. In other words, the successive fancy yarn segments would be identical. However, because of the variations in the manufacturing process, the raw materials and the manufacturing conditions such an optimum product which has optimum quality characteristics is elusive. However, it is possible to manufacture a product which has an acceptable level of variation for its characteristics. Usually, the properties of such a product would have normal distributions if the process was statistically controlled.

3.15 Material, Machine Settings and the Experimental Procedures Used to Evaluate the Impact of the Core Thread Tension on the Structure and Quality of Multi-thread Fancy Yarn

All the fancy yarns were made using only one thread effect which was a two-ply lambswool thread (R120/2 tex). The mean value of its bending stiffness was B_e=2.518 g mm^2 and the standard deviation SD=0.966 g mm^2. The core thread was an undyed two-ply cotton yarn (R144/2 tex). Its mean bend stiffness was B_c= 2.238 g mm^2 and SD=0.521 g mm^2. The binder was a 29.5 tex rotor-spun cotton yarn. The machine settings and the yarn structural parameters are given in Table 13. The overfeed ratio was low, i.e. η=150%. This meant that there was only 50% extra length of the effect thread in comparison with the core thread within the fancy yarn structure. The number of was also low, i.e. W=150 wpm. Due to the low η and W, the fancy yarns would be as light as possible.

The tension of the core thread was measured using a Wira yarn tension meter (type no. 676 ser. no. 4/439 with a gradation scale from 0 to 120 grams). Measurements were accomplished, while making the fancy yarns on the hollow-spindle machine, in accordance with the operating instructions of the same tension metre.

Table 13: Machine Settings to Test the Impact of Tensioning the Core Thread on the Structure of Bouclé Yarn

Fancy Yarn	Machine Settings			
	Tension of Core Thread, g	DS: Delivery Speed m min^{-1}	SS: Supply Speed m min^{-1}	RS: Rotational Speed rpm
Yarn 1	0[18]	30	45	4500
Yarn 2	5			
Yarn 3	8			
Yarn 4	17			
Yarn 5	21			

The fancy yarns were tested to define the ones which are believed to be bouclé and the one which are not bouclé. To assess the quality of those fancy yarns, both qualitative, subjective approach and quantitative, objective approach were used. The subjective approach was descriptive while the objective approach was based on measuring the Number of Fancy Profile, the Size of Fancy Profile, the Shape Factor of Fancy Yarn (ShF), the Circularity Ratio of Fancy Profile (CR %), and statistical techniques.

To measure the area and the circularity ratio of the fancy profiles of the fancy yarns made, 16 specimens were systematically sampled and used. The sampling distance was 60 cm rather than 20 cm. In doing so, the accuracy of the study remained valid and statistically justified. To measure the number of the fancy profiles, 10 measurement rather than 15, were taken, but the unit length used increased to one metre rather than 1 decimetre.

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[18] The value obtained was zero because the pointer of the tension device did not move while taking the measurements. However, since the input yarn was moving forward, it must be subjected to some level of Tension. This Tension must have been small so as not be detected by the Wira device.

3.16 Material, Machine Settings and the Experimental Procedures Used to Assess the Influence of Width of the Spinning Triangle on the Structure of Bouclé Yarn

The materials of this experiment were as follow:

- The effect thread was a 67 tex wool thread;
- The core thread was a three-ply cotton thread (R72/3 tex); and
- The binder was a nylon multi-filament (R14.5/77 tex).

The tension of the core thread while running the machine was *approximately* zero. The supply speed of the machine was 54 m min^{-1}, the delivery speed was 30 m min^{-1} and the rotational speed was 5700 rpm. Therefore, the number of wraps was W=5700/30=190 wpm, while the overfeed ratio was η= (54/30) ×100=180%. The widths of the base of the spinning triangle were 4.5, 7.5, 10, 13, and 16 mm. Due to the variability of the manufacturing process and the vibration of the machine parts, the previous values were continuously changing within ranges ±0.5 mm. Further, those values were limited by the width of the upper supply roller.

15 specimens were sampled systematically to count the number of the bouclé and semi-bouclé profiles per dm and the sampling distance was 2 metres. Further 15 specimens were also sampled systematically to measure the area and the circularity ratio of the fancy profiles. The sampling distance between each two profiles selected was 60 cm.

3.17 Material and Experimental Procedure Used to Assess the Variability of the Machine

The materials used to make the bouclé yarns in this experiment were:

- The core of the bouclé yarns was an undyed, two-ply blended lambswool/cotton thread (R120/2 tex). The mean value of bending stiffness of this thread was B_c=3.662 g mm^2 and the standard deviation was SD= 1.774 g mm^2.

- The binder was a nylon multi-filament (R14.5/77 tex).
- The effect component was made by two identical threads; each of which was an two-ply lambswool thread (R120/2 tex). The mean value of bending stiffness of each of them was B_e= 2.518 g mm^2 while SD= 0.966 g mm^2.

Six bouclé yarns were made for this experiment. Table 14 gives the machine settings, the number of wraps (W) and the overfeed ratio (η%) used.

Table 14: Machine Settings and Yarn Structural Parameters Used to Assess the Variability of the Hollow-spindle Machine

Bouclé Yarn	Time from Start-up of the Machine min	Delivery Speed m min^{-1}	Supply Speed m min^{-1}	Rotational Speed rpm	Number of Wraps wpm	The Overfeed Ratio %
yarn 1	0	30	60	5500	183.3	200
yarn 2	30					
yarn 3	60					
yarn 4	90					
yarn 5	185					
yarn 6	205					

3.18 Material, Machine Settings and the Experimental Procedures Used to Study the Interaction between the Bending Stiffness of the Core Thread and the Bending Stiffness of the Effect Threads

The material used to make the bouclé yarns are given in Table 15.

Table 15: Materials Used to Study the Interaction of the Bending Stiffness of the Core Thread and the Effect Threads

Yarn Function	Levels of Factors	Material Types	Number of Threads	Linear Density tex	Bending Stiffness B (g mm^2)	
					Average	Standard Deviation
Binder component	*	Polyester multi-filament	1	16.7/34	*	*
Core component (Factor C)	**C1**	Cotton	1	R72/3	0.777	0.242
	C2	Cotton/Lambswool	1	R120/2	4.507	1.591
	C3	Stiff Acrylic, multi-filament	1	140	22.514	6.75
Effect component (Factor E)	**E1**	Flexible acrylic	2	R72/2	1.201	0.387
	E2	Purewool, (Glenshear)	2	R120/2	3.859	1.161
	E3	Stiff acrylic, multi-filament	2	140	21.279	7.353
Core component	Confirmation yarn 1	Lambswool	1	R120/2	3.340	0.839
Effect component		Natural wool	2	R195/2	7.272	1.578
Core component	Confirmation yarn 2	Cotton	1	R126/3	1.453	0.361
Effect component		Soft Shetland wool	2	R220/2	9.392	2.737

This table also shows how those materials were chosen for the different levels of the factors of this experiment. In order to confirm the results of this experiment, the same machine settings and yarn structural parameters were used to make two confirmation bouclé yarns. Threads different in stiffness were used to make the fancy element of the resultant yarns.

The experimental work for this experiment is different from the experimental work given in Sections 3.10 and 3.11 in the following points:

- the types of material used for the core component, the effect component and the binder;
- the values of the overfeed ratio and number of wraps. In this experiment, they are η= 220% and W=280wpm;
- the speeds of the hollow-spindle spinning machine. The speeds in this experiment were RS=8400 rpm and SS=66 m min^{-1} (DS=30 m min^{-1}); and
- the number and nature of the trials of this experiment which are based on the technique of the Design of Experiments (DOE) as shown in the following section.

Therefore, repetition was avoided. Since the threads varied considerably, in this experiment, in terms of linear density, it was difficult to choose a number of wraps suitable to all thicknesses. Further, this experiment was based on a full factorial design of two factors and three levels each. Therefore, the number of runs was 9. The factors were factor[19] E=B_e and factor C= B_c. The full factorial design was an orthogonal array [19]. Thus, the influence of noise factors was avoided. Examples of noise factors may be temperature and humidity. The trials of this experiment were randomised to minimise the influence of variation in the levels of factors, in particular the speeds of the machine, on the results.

To test the bouclé yarns, a systematic method of sampling was followed. Therefore, representative samples were obtained. 31 measurements were made to calculate the Size of Bouclé Profile. 15 measurements were made for the Number of Bouclé Profiles per decimetre. The data collected from the nine runs of the experiment were used to estimate the influence and interaction of bending stiffness of the core thread and the effect threads on the structure and quality characteristics of the resultant bouclé yarns.

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[19] Symbols E and C were needed for the use of DOE on Minitab, while B_e and B_c were terms used to refer to bending stiffness as a mechanical property of the input threads.

This was conducted using Minitab and *response tables* [19] as shown in the following section.

3.19 The Experimental Designs of this Research

The technique of Design of Experiments [19] was used to assess the influence of more than one factor at one time on the structure of bouclé yarn. Not only the experimental designs used were full factorial designs with all possible combinations of factor levels, they were also robust orthogonal arrays. Therefore, they were expected to help in protecting the estimated value of each factor from the artificially large or small influence of other factors [19]. The trials of the experiments were randomized to minimise relation bias and to minimise the chance for some factors to change with time. However, the trials were not replicated. Three levels were decided for each factor and those levels were identified by practical means, e.g. the speeds of hollow-spindle spinning machine, the structural parameters of bouclé yarn, the availability of materials, the suitability of the machine speeds to make a bouclé yarn, etc. Although temperature and the relative humidity were uncontrolled factors, the input yarns themselves were taken from standard atmospheric conditions. Additionally, the final fancy yarns made were reconditioned in standard atmospheric conditions as stipulated by the BSI ISO Standard 139:2005 before any further testing. The experimental designs were generated using Minitab® 17.1.0.0. The number of trials was k^n trials (where k was the number of factors of each experiment and n was the number of levels decided for each factor).

The experimental design used to estimate the interaction between the bending stiffness of the core (B_c) and the bending stiffness of the effect thread (B_e) is given in Table 16. The number of the factors was k=2 and three levels were designated for each factors, so the number of trials was $k^n=2^3=9$ trials. Symbols C1, C2, and C3 were used in the Minitab interface for the levels of factor B_c, while symbols E1, E2 and E3 were used for the levels of factor B_e. So, the term C1&E1 refers to the fancy yarn made by using the first level of bending stiffness of the core component (C1) and the first level of bending stiffness of the effect component (E1), and so forth for the other symbols.

Table 16: The Experimental Design Used to Estimate the Interaction between the Bending Stiffness of the Core Thread and the Bending Stiffness of the Effect Thread

Random-Order Trial number	Standard-Order Trial Number	Level of Factor B_c	Level of Factor B_e	Yarn Designation
5	1	C1	E1	C1&E1
6	2	C1	E2	C1&E2
4	3	C1	E3	C1&E3
2	4	C2	E1	C2&E1
3	5	C2	E2	C2&E2
1	6	C2	E3	C2&E3
8	7	C3	E1	C3&E1
9	8	C3	E2	C3&E2
7	9	C3	E3	C3&E3

The influence of factors B_e and B_c on any fancy yarn property, e.g. the Size of Fancy Profiles, was calculated using a *response table*. It was possible to use the Minitab® 17.1.0.0 programme to do a similar thing. However, by experience, it is known that response tables outdo the Minitab software because they show the influence of each factor level on the estimated value of fancy yarn property. An example of a response table is provided in Table 17 for the Size of Bouclé Profiles. So, the method used to calculate the influence of the individual levels of the factors on the Size of Bouclé Profiles can be explained using Table 17 as follows:

By considering the standard order of the trials, Trial 1 of this experiment was conducted by using levels C1 and E1. The fancy yarn resulted had fancy profiles with an average area of 10.29 mm^2. This value was used in column 3 and row 1 of Table 17 to match the standard order of the trials. The same value was also used in the same row in column 4 and 7 corresponding to C1 and E1 respectively. The same procedure was used for the other trials by entering the average values of area of fancy profile which resulted from the trials. Consequently, each column of each level of the factors C and E had three values of the area of fancy profile. These values were added together in row 10 (i.e. Total), then averaged in row 12. So, the average values of area which corresponded to the specific levels of the factors were calculated in row 12.

The influence of any factor on the size of the profiles was estimated by calculating the differences in the values of row 12. For example, Level C1 made 12.4 mm^2 fancy profiles, while Level C2 made an 11.52 mm^2 fancy profile. Therefore, the contribution of factor B_c when its value changed from level C1 to level C2 was 11.52-12.4=-0.87 mm^2. Identical procedure was used for all factors and levels regarding the other fancy yarn properties. Therefore, the influence of each factor, when its value changed from a level to another, was calculated in rows 13, 14 and 15 of Table 17.

A similar *response table* may also be used to analyse the variability of the Size of Fancy Profile. To do so, it was required to use the values of either the average or standard deviation of bending stiffness, based on the expected source of variation, and the values of standard deviation of the Size of Fancy Profile which resulted from the trials.

The value in row 12 and column 3 of Table 17 is the average profile area which resulted from this experimental design as a whole. This value may also be called the *constant of the process* regarding the (average) Size of Bouclé Profile. Further, another constant of the process related to variation in Size of Bouclé Profile may also result. Those two constants were used to estimate the *Coefficient of Variation* CV *% of the process* regarding the Size of Bouclé Profile. An identical approach may be used for the fancy yarn properties.

Table 17: Response Table for Estimating Size of Bouclé Profile Depending on Value of Bending Stiffness of the Core Thread and the Effect Thread

Column / Row	1	2	3	4	5	6	7	8	9
	Randomised-Order Trail Number	**Standard- Order Trial Number**	**Size of Bouclé Profile of the Trial, mm^2**	**Level of Factor C**			**Level of Factor E**		
				1	**2**	**3**	**1**	**2**	**3**
				0.777 g mm^2	**4.507 g mm^2**	**22.514 g mm^2**	**1.201 g mm^2**	**3.859 g mm^2**	**21.279 g mm^2**
1	**5**	**1**	10.29	10.29			10.29		
2	**6**	**2**	11.93	11.93				11.93	
3	**4**	**3**	14.98	14.98					14.98
4	**2**	**4**	9.83		9.83		9.83		
5	**3**	**5**	10.59		10.59			10.59	
6	**1**	**6**	14.15		14.15				14.15
7	**8**	**7**	12.03			12.03	12.03		
8	**9**	**8**	10.24			10.24		10.24	
9	**7**	**9**	13.15			13.15			13.15
10	**Total (mm^2)**		107.19	37.2	34.57	35.42	32.15	32.76	42.28
11	**Number of Values**		9	3	3	3	3	3	3
12	**Average (mm^2)**		11.91	12.4	11.52	11.80	10.71	10.92	14.09
13	**Effect of Factor from Level 1 to Leve1 2 (mm^2)**			-0.87			0.20		
14	**Effect of Factor from Level 2 to Level 3 (mm^2)**				0.28			3.17	
15	**Effect of Factor from Level 1 to Level 3 (mm^2)**			-0.59			3.37		

3.20 List of the Equipment Used

The equipment used to complete this research were:

1. A hollow-spindle machine (Gemmill & Dunsmore #3);
2. The Improved Bending Frame (prepared by the researcher himself);
3. A Wira yarn tension meter (type no. 676 ser. No. 4/439) with a gradation scale from 0 to 120 grams;
4. An electronic scale (Oertling) with 0.0001 gram sensitivity;
5. A manual guillotine (rexel SmartCut A525pro);
6. A laser cutter (FB Series Laser Cutter, CadCam Technology LTD, UK);
7. A Kawabata's Pure Bending Tester KES-FB-2 (Japan);
8. A digital camera (Fujifilm FinePix HS20 EXR, 16MP, 30x Optical Zoom, 3-inch LCD;
9. A digital camera (Fujifilm FinePix A170 ,10MP, 3x Zoom 2.7 inch LCD;
10. A manual winding reel (DOODBRAND & CO. LTD, England); and
11. A digital camera (OLYMPUS Soft Imaging Solutions GmbH) mounted on a microscope (NOVEX, Holland) and linked to a PC. This Camera is operated by the image analysis software analySIS FIVE which is installed on a computer.

Chapter 4: Theoretical Modelling of Multi-thread Bouclé Yarn and Similar Multi-thread Fancy Yarn

4.1 Introduction

It was shown in Section 2.13.1 that a simple geometrical model for fancy yarns that have multi-thread structure, made by doubling, twisting or wrapping is not yet available. Therefore, introducing such a model will be valuable for understanding doubled fancy yarns and other types of multi-thread fancy yarn. Further, the benefit of such a model is that it may help in recreating a copy of an already made fancy yarn if the structural parameters, such as the overfeed ratio or the number of wraps, are unknown. A further benefit is that such a model may be used to predict the structure and visual appearance of multi-thread fancy yarn after changing the overfeed ratio or the number of wraps. To make it simple, Such a model should be based on a small number of variables.

4.2 Nomenclature

m	is the number of the sinusoidal sections
n	is the number of the helical sections
$\lambda = m + n$	is the total number of sections in a basic building unit of the structure
R_e	is the radius of the effect thread
R_c	is the radius of the core thread
H_1	is the height of the helical sections
H_2	is the height of the sinusoidal sections
L_1	is the length of the core thread in the sinusoidal part of the structure, corresponding to one sine wave, i.e. also corresponds to one helix of the binder

L_2 is the length of the core thread in the helical part of the structure, corresponding to one helix, i.e. also corresponds to one helix of the binder

$L_c=L_1 + L_2$ is the length of the core thread corresponding to one building unit of the model

L is the length of the ultimate fancy yarn

W is the number of wraps of the binder

L_{e1} is the length of the effect thread in the sinusoidal part of the structure corresponding to one sine wave

L_{e2} is the length of the effect thread in the helical part of the structure corresponding to one helix

$L_e=L_{e1} + L_{e2}$ is the length of the effect thread corresponding to the basic building unit, i.e. L_e corresponds to L_c

ShF is the Shape Factor of Fancy Yarn

E (Φ, k) is the incomplete elliptic integral of the second kind

$\eta = L_e/L_c$ is the overfeed ratio, i.e. $\eta\ \% = (L_e/L_c)\times 100$

$\propto$ is a symbol which denotes a positive proportional relationship between two parameters

Δ is used to refer for a change in a parameter or a variable

A is the amplitude of a sine wave in its general form

4.3 Assumptions

The geometrical model of multi-thread fancy yarn of this work covers several types of multi-thread fancy yarns, such as bouclé yarns, semi-bouclé yarns, gimp yarns, wavy yarns, overfed fancy yarns and their commercial variants. The multi-thread fancy yarn was considered to have at least three components- the core thread, the binder thread and the effect thread. It may be possible to extend this model to account for multi-thread fancy yarns made with two or three effect threads.

In developing the mathematical model, it was assumed that:

(1) Each of the components had a circular cross-section.
(2) The radius of circular cross-section of each of the components was constant.
(3) The density and the packing density of the fibres were uniform and constant along each thread axis.
(4) The threads were neither extensible nor compressible.
(5) The bending stiffness of the effect thread was uniformly distributed along the effect thread axis. Therefore, the effect thread may bend in a uniform curvature.
(6) The core thread was always straight. Applying a suitable level of tension on this component while making the fancy yarn may secure such an assumption. This assumption was needed to make the model simple; otherwise, the core thread would assume a spiral configuration.
(7) The bouclé yarn had more than one type of fancy profile, in particular bouclé projections and sigmoidal sections.

The basic building unit of the structure of multi-thread fancy yarn was modelled visually, as shown in Figure 9.

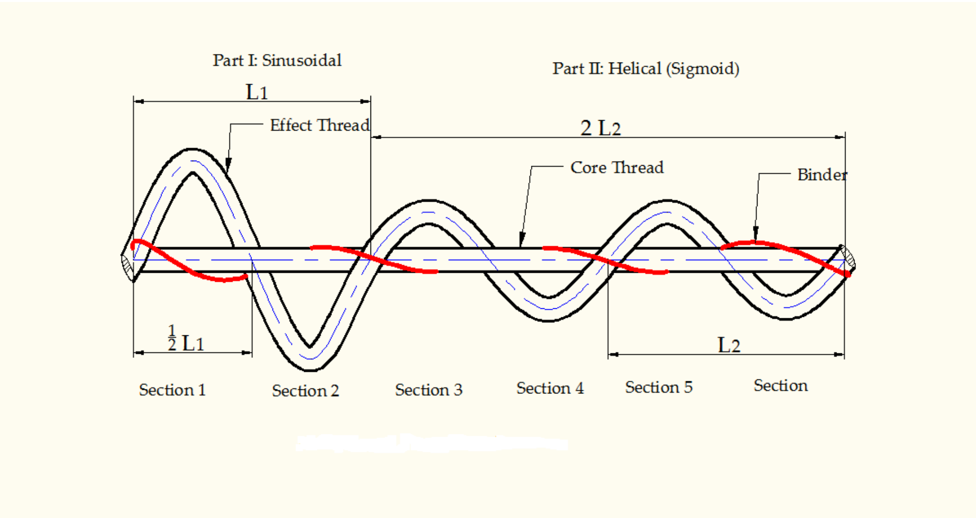

Figure 9: Graphical Model of the Structure of Multi-thread Fancy Yarn

This unit was assumed to repeat regularly along the fancy yarn axis. Taken into account the schematic diagram in Figure 9, the multi-thread fancy yarn had two parts:

- Part 1: a sinusoidal part, which was formed by the bouclé profiles. This part may extend over *m* sections. Though, it was only visualised in Figure 9 to extend over 2 sections.
- Part 2: a helical part or the sigmoidal part of the fancy yarn. This part may extend over *n* sections. It was shown in Figure 9 that the helical part had extended over 4 sections, though.

In an industrial situation, and while making fancy yarns on hollow-spindle spinning machines, the sigmoidal part may form initially as a helix within the First Spinning Zone of the machine, then it may deform locally and slightly by the pressure of the binder (helix) at the points of contact. Such a minor alteration usually accounts for obtaining the sigmoidal sections of multi-thread fancy yarn. It is believed that such a local alteration in the configuration of the helical part may not affect the accuracy of the model because the length of the helix itself may not change, neither may its diameter at the middle between the contact points. A precise account of such a minor deformation may render the model over-complicated, thus it may lose its practical importance.

4.4 Model Development

To develop a mathematical model of the whole fancy yarn, its two parts were firstly modelled, then the resulting models were combined. The objective was to build up models for the length of the effect thread and the overfeed ratio for both parts of the structure proposed. The independent variables of the models were the number of wraps of the binder (W), the height of the fancy projections (H_1 and H_2) and the length of the core thread (L_c).

4.4.1 Part 1: Sinusoidal Part

This part is depicted in Figure 10. It was assumed that the sinusoidal function representing this part started from the origin of a co-ordinate system (not shown in the figures). It was also assumed that the core thread axis coincided with the *x* axis.

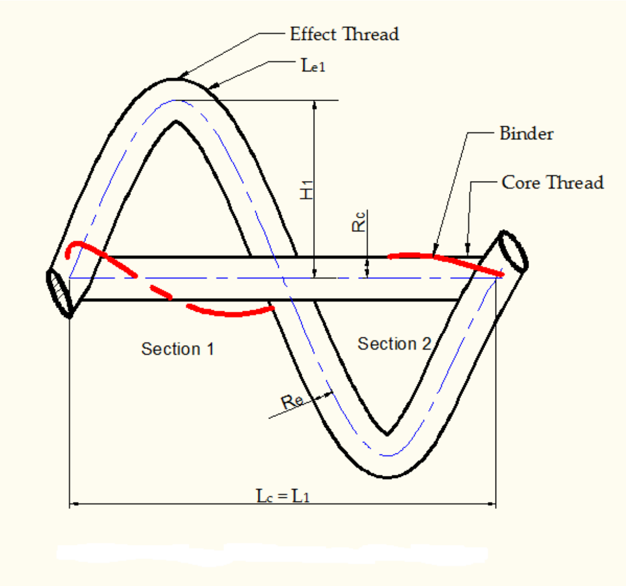

Figure 10: Visual Model of the Sinusoidal Part of Bouclé Yarn Structure

The sinusoidal function (i.e. representing a sine wave) was given by the equation:

$$y = A\sin(\frac{2\pi x}{L_1}) \qquad (4.1)$$

Where A is the amplitude of a sine wave in its general form and L_1 is the length of the core thread in the sinusoidal part of the model.

It was supposed that L_1=L_2 which both are the length of one segment of the fancy yarn where each segment corresponded to one turn of the binder; thus, each segment of the fancy yarn had two sections. The sections were determined between the points of contact of the core, the binder and the effect thread. It was assumed that H_1 represented the maximum height of the sinusoidal part of the effect thread, therefore A= H_1. The length of the effect thread of this part (L_{e1}) was the length of a sine wave. Generally, integrating function *y* over *x* may give the length of a sine wave, i.e. the length of the effect thread. The integration required to calculate the length between two definite boundaries *c* and *d* of *x* in its general form is:

$$L_{e1} = \int_c^d \sqrt{1 + (\frac{dy}{dx})^2}\, dx \tag{4.2}$$

The derivative of y over *x* is:

$$\frac{dy}{dx} = A\,\frac{2\pi}{L_1}\cos(\frac{2\pi\, x}{L_1}) \tag{4.3}$$

To make the calculus simpler, it was assumed that $= \frac{2\pi}{L_1}$. Therefore, the indefinite form of the integration given in equation (4.2) was firstly represented by the equation[20]:

$$\int \sqrt{1 + A^2B^2\cos^2(Bx)}\ dx = \frac{\sqrt{A^2B^2\cos(2Bx)+A^2B^2+2}\ \ E(Bx, \frac{A^2B^2}{A^2B^2+1})}{B\sqrt{\frac{A^2B^2\cos(2Bx)+A^2B^2+2}{A^2B^2+1}}} + constant \tag{4.4}$$

Where: *E* (Φ, k) is an incomplete elliptic integral of the second kind. *E* was given by the equation:

$$E\ (\Phi, k) = \int_0^{\phi} \sqrt{1 - k^2\, sin^2\,\theta}\ \ d\phi \tag{4.5}$$

Instead of integrating equation (4.5) to obtain a value for *E*, it was possible to estimate the value of *E* numerically between the boundaries from $c = 0$ to $d = L_1$.

The definite integration of equation (4.4) was calculated between the boundaries from $c = 0$ to $d = L_1$; thus:

$$L_{e1} = \int_0^{L_1} \sqrt{1 + \left(\frac{2\pi H_1}{L_1}\right)^2 cos^2\left(\frac{2\pi\, x}{L_1}\right)}\, dx = \left[\frac{\sqrt{\frac{4\pi^2H_1^2}{L_1^2}\cos(\frac{4\pi x}{L_1}) + \frac{4\pi^2H_1^2}{L_1^2} + 2}\ \ E\,(\frac{2\pi x}{L_1}, \frac{\frac{4\pi^2H_1^2}{L_1^2}}{\frac{4\pi^2H_1^2}{L_1^2}+1})}{\frac{2\pi}{L_1}\sqrt{\frac{\frac{4\pi^2H_1^2}{L_1^2}\cos(\frac{4\pi x}{L_1}) + \frac{4\pi^2H_1^2}{L_1^2}+2}{\frac{4\pi^2H_1^2}{L_1^2}+1}}}\right]_0^{L_1} \tag{4.6}$$

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[20] The integrations and numerical estimations of this chapter were completed and calculated online using a website called Wolfram MathWorld found at www.wolframalpha.com, or mathworld.wolfram.com.

Since $E(0,x)=0$, L_{e1} became:

$$L_{e1} = \frac{\sqrt{\frac{4\pi^2 H_1^2}{L_1^2}\cos(\frac{4\pi L_1}{L_1})+\frac{4\pi^2 H_1^2}{L_1^2}+2}\ E\left(\frac{2\pi L_1}{L_1},\frac{\frac{4\pi^2 H_1^2}{L_1^2}}{\frac{4\pi^2 H_1^2}{L_1^2}+1}\right)}{\frac{2\pi}{L_1}\sqrt{\frac{\frac{4\pi^2 H_1^2}{L_1^2}\cos(\frac{4\pi L_1}{L_1})+\frac{4\pi^2 H_1^2}{L_1^2}+2}{\frac{4\pi^2 H_1^2}{L_1^2}+1}}} - 0 \tag{4.7}$$

or

$$L_{e1} = \frac{\sqrt{\frac{4\pi^2 H_1^2}{L_1^2}\cos(4\pi)+\frac{4\pi^2 H_1^2}{L_1^2}+2}\ E\left(2\pi,\frac{\frac{4\pi^2 H_1^2}{L_1^2}}{\frac{4\pi^2 H_1^2}{L_1^2}+1}\right)}{\frac{2\pi}{L_1}\sqrt{\frac{\frac{4\pi^2 H_1^2}{L_1^2}\cos(4\pi)+\frac{4\pi^2 H_1^2}{L_1^2}+2}{\frac{4\pi^2 H_1^2}{L_1^2}+1}}} \tag{4.8}$$

Since $\cos(4\pi)=1$ and $L_1 = \frac{1}{W}$, where W is the number of wraps of the binder, the previous equation became:

$$L_{e1} = \frac{\sqrt{4\pi^2 H_1^2 W^2+4\pi^2 H_1^2 W^2+2}\ E\left(2\pi,\frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2+1}\right)}{2\pi W\sqrt{\frac{4\pi^2 H_1^2 W^2+4\pi^2 H_1^2 W^2+2}{4\pi^2 H_1^2 W^2+1}}} \tag{4.9}$$

Further modifications made it:

$$L_{e1} = \frac{\sqrt{2(4\pi^2 H_1^2 W^2+1)}\ E\left(2\pi,\frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2+1}\right)}{2\pi W\sqrt{2\,\frac{(4\pi^2 H_1^2 W^2+1)}{4\pi^2 H_1^2 W^2+1}}} \tag{4.10}$$

or for one phase of the sinusoidal wave (i.e. one yarn section) which has length ½L1,

$$L_{e1} = \frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{4\sqrt{2}\,\pi\, W} \tag{4.11}$$

Where Le1 in equation (4.11) is the length of only one sinusoidal section (i.e. one phase of the sine wave). However, because L_{e1} may usually extend over *m* section of the sinusoidal part and not only two sections, the previous equation was modified to take the following general form:

$$L_{e1} = \frac{m}{2}\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\, W} \tag{4.12}$$

4.4.2 Part 2: The Helical Part (i.e. Sigmoidal Part)

The helical part of the graphical model is shown in Figure 11. Taking into account the schematic drawing in this figure and Figure 12, and depending on *Pythagoras* Theorem, the following equation was obtained:

$$L_{e2} = \sqrt{L_2^2 + 4\pi^2 H_2^2} \tag{4.13}$$

where H_2 is the width of the spiral.

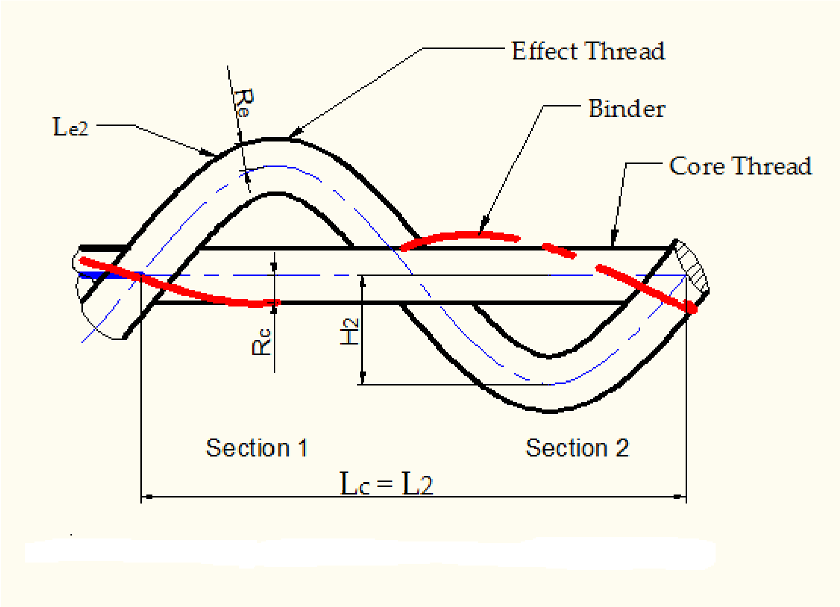


Figure 11: Sigmoid Part (i.e. Helix) of Bouclé Yarn Structure

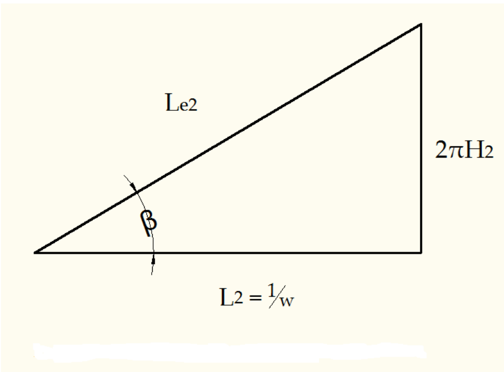


Figure 12: Helix Triangle and Helix Angle β

Since it was assumed that the lengths of one section in the sinusoidal part and one section in the helical part of the yarn were equal, i.e. $L_1 = L_2 = \frac{1}{W}$, it was possible to write:

$$L_{e2} = \sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} = \frac{\sqrt{1+W^2 4\pi^2 H_2^2}}{W} \tag{4.14}$$

Therefore, the length L_{e2} for only one spiral section (that is, half the length of a helix) is:

$$L_{e2} = \frac{1}{2}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} = \frac{\sqrt{1+4\pi^2 W^2 H_2^2}}{2W} \tag{4.15}$$

Since L_{e2} may usually extends over more than only one or two fancy yarn sections, i.e. n sections, the previous equation was modified to take the form:

$$L_{e2} = \frac{n}{2}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} = \frac{n}{2}\,\frac{\sqrt{1+4\pi^2 W^2 H_2^2}}{W} \tag{4.16}$$

Therefore, the total length of the effect thread became: $L_e = L_{e1} + L_{e2}$ or

$$L_e = \frac{m}{2}\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\; E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\, W} + \frac{n}{2}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} \tag{4.17}$$

The overfeed ratio of the effect thread was given by the following equation:

$$\eta = \frac{L_e}{L_c} \tag{4.18}$$

However, if L is the length of the fancy yarn which corresponds to L_e (i.e. it is made by both the sinusoidal and the helical part), and L_c is the length of the core thread which corresponds to L_e:

$$L_c = L = L_1 + L_2 = \frac{m}{2W} + \frac{n}{2W} = \frac{\lambda}{2W} \tag{4.19}$$

Therefore:

$$\eta = \frac{\frac{m}{2}\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\; E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\, W} + \frac{n}{2}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2}}{\frac{\lambda}{2w}} \tag{4.20}$$

or

$$\eta = \frac{m\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\,\lambda} + \frac{nW}{\lambda}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} \quad (4.21)$$

4.5 The Form of the Model which is Suitable for Hollow-spindle Machines

Depending on the technology used to make multi-thread fancy yarns, the previous model may have a new form. For instance, when the hollow-spindle system is used, the sinusoidal section is expected to extend over one binder wrap, rather than half a wrap. This sinusoidal section is also expected to be tilted rather than being a projection in a plane. Similarly, the helical sections were observed to extend over a whole wrap, rather than half a wrap. Therefore, the length of the core thread became $L_c = \lambda/W$ and equations 4.12, 4.16, 4.17 and 4.21 were modified respectively as follow:

$$L_{e1} = m\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\,W} \quad (4.22)$$

$$L_{e2} = n\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} = \frac{n}{W}\sqrt{1 + W^2 4\pi^2 H_2^2} \quad (4.23)$$

$$L_e = m\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\,W} + n\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} \quad (4.24)$$

$$\eta = m\,\frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}\ E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right)}{2\sqrt{2}\,\pi\,\lambda} + \frac{nW}{\lambda}\sqrt{\frac{1}{W^2} + 4\pi^2 H_2^2} \quad (4.25)$$

4.6 Discussions

The model for the structure of multi-thread fancy yarn was assumed to have *m* bouclé profiles and *n* sigmoid profiles. Therefore, the total number of sections was $\lambda = m + n$. Several different variants of the structure having *m* number of bouclé profiles were possible. This is because the location of sections m and n are interchangeable. Examples of those alternative forms are given in Figure 13 when m=2 and n =4. In the general form of the geometrical model, each wrap of the binder made two sections of the fancy yarn. Further, the sections m and n are variables, and, accordingly, their values define the resultant type of multi-thread fancy yarn. In all those case, all the previous calculations and equations will remain valid.

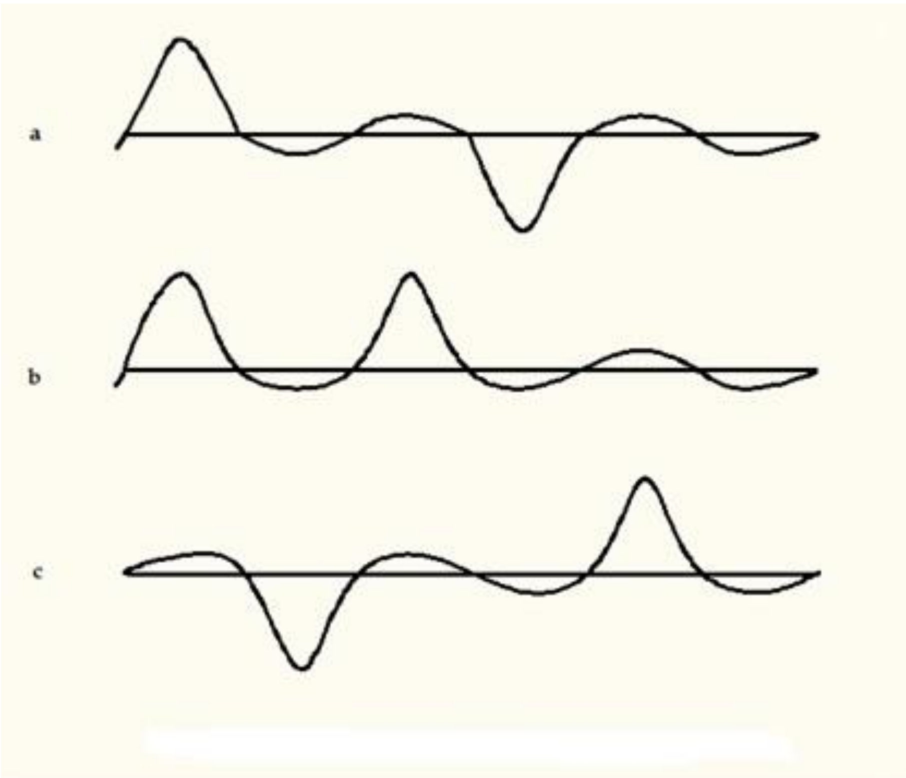


Figure 13: Examples of Variants of Multi-thread Fancy Yarn Structure

The possibilities of the structure can be given mathematically in a *combination* formula C (λ, m) which takes the general form as follows:

$$C(\lambda, m) = \frac{\lambda!}{m!\,(\lambda - m)!} = \frac{\lambda!}{m!\,n!} \tag{4.26}$$

Where, for example, n factorial $n! = n\times(n-1)\times(n-2)\times(n-3)\times \ldots\times 1$.

For instance, when $\lambda = 6$ and $m = 2$, the number of possibilities was:

$C(6,2) = \frac{6!}{2!(6-2)!} = \frac{6!}{2!\,4!} = 15$ variants of the previous structure.

It is worth noting that a *combination* in statistics is a way of selecting several things (e.g. the two sinusoidal sections in the case of this model) out of a larger group (e.g. the total number of sections of the proposed structure, i.e. 6 in Figure 9). Order of results is not important in the case of combination. This meant that whether the positive or the negative element of the sinusoidal wave (i.e. sinusoidal part) appeared in *section one* of the fancy yarn structure, the structure remained, or was still considered to be, the same. The thing that became different was the direction at which the structure was looked at, i.e. from above or from below. If the order was thought to be important, then *permutation* (which is a statistical concept to estimate probability) must have been used.

4.6.1 Types of Fancy Yarn Represented by the Geometrical Model

With reference to the graphical model in Figure 9 and the equations for L_e, there were eight cases to be considered:

(1) When $\lambda = m$; $n = 0$, the structure had only sinusoidal sections and the fancy yarn was a *pure bouclé* yarn.
(2) When $m >> n$, the fancy yarn was recognized as a *bouclé* yarn.
(3) When $m \geq n$, the fancy yarn was recognized as a *semi-bouclé* yarn.
(4) When $m < n$, the fancy yarn was called an *overfed* fancy yarn.
(5) When $m << n$, the fancy yarn was called a *gimp yarn derivative*.
(6) When $m = 0$; $H_2 = R_c + R_e$ the fancy yarn was a *spiral* yarn.
(7) When $m = 0$; $H_2 > R_c + R_e$ and $H_2 > ½\, L_2$ the fancy yarn was a *gimp* yarn.
(8) When $m = 0$; $H_2 > R_c + R_e$ and $H_2 < ½\, L_2$ the fancy yarn was *wavy* yarn.

Where R_c and R_e are radii of the core thread and the effect thread respectively.

4.6.2 Relationship between *n* and *m* and between H_1 and H_2

Since $\lambda = n + m$, if λ was fixed, an increase in *m* means a reduction in *n*, and vice versa. Heights H_1 and H_2 were inversely related for a specific length of the effect thread L_e. An increase in the former leads to a reduction in the latter, and vice versa.

4.6.3 The Influence of Changing the Overfeed Ratio (η)

By considering equation 4.17, there were several scenarios. In the first scenario, suppose L_c, W, *m* and *n* were all fixed, so an increase in one of, or both, H_1 and H_2 may lead to an increase in L_e, and vice versa. If η to be increased, L_e must be increased. Therefore, depending on the previous preconditions, H_1 and H_2 should increase accordingly. Consequently, the average size of the fancy projection should increase.

In the second scenario, one may expect the height of the sinusoid to remain unchanged, i.e. H_1=const. In this case, an increase in L_e may result in an increase in the width of the spiral sections (H_2) and they may appear bulkier on the final fancy yarn. If H_2 increases sufficiently to become equal to H_1, the whole sigmoid sections of the fancy yarn may become *approximately* similar to the bouclé sections after being deformed by the binder. This means that the number of bouclé and semi-bouclé projections increases. Further, during manufacturing of fancy yarn, the increase in either H_1 or H_2 may not be regular. One may expect the height of the spiral sections which are adjacent to the sinusoidal sections to increase. However, it may not reach the already greater height of such sinusoidal sections. So, the variation in height of the fancy profiles increases.

The last two scenarios may happen in practice for practical reasons related to the technology used to make the multi-thread fancy yarn. For example, considering hollow-spindle spinning machines, the main constraints are the number of wraps of the binder, the limitation of space available for the bent effect thread (because of the balloon of the binder during unwinding it off the hollow-spindle package), and the variability of stiffness of the effect thread. Unless the effect thread is unnecessarily stiff, those constraints do not allow excessive heights of the sinusoidal waves to form. The changes in the height ΔH_1 is expected to be relatively small. However, to increase the overfeed ratio, there must be an increase in the length of the effect thread, i.e. ΔL_e.

Therefore, and based on the constraints stated above, there is a chance to increase H_2 more than H_1, i.e. $\Delta H_2 > \Delta H_1$. Such a prediction can happen in practice locally in some sections rather than over the whole sigmoid parts. Subsequently, more semi-bouclé projections are expected to form but with shapes that not exactly resembling the sine waves. Further, the height of such new semi-bouclé projections might not reach H_1. Therefore, it can be stated that:

if λ is constant and $\Delta\eta > 0$, then $\Delta m > 0$, $\Delta n < 0$

where m, n usually remains positive integers.

These conclusions can be inferred mathematically from equation 4.16 as follows.

The length $L_{e2} = \frac{n}{2} \frac{\sqrt{1+4\pi^2 W^2 H_2^2}}{W}$ may be rewritten as:

$$n = \lambda - m = \frac{2\, W\, L_{e2}}{\sqrt{1+4\pi^2 W^2 H_2^2}} \tag{4.27}$$

or

$$m = \lambda - \frac{2\, W\, L_{e2}}{\sqrt{1+4\pi^2 W^2 H_2^2}} \tag{4.28}$$

Suppose L_c, W, H_1 are fixed, then λ and L_{e1} do not change. If η to be increased L_{e2} must increase. Consequently the second term of equation (4.28) becomes smaller in value than its current value, thus m increases in value. Additionally, m becomes higher in value if H_2 of the sigmoid sections increases to become approximately close in value to H_1. This case accounts for semi-bouclé sections. If m increases n must decreases.

4.6.4 The Influence of Changing the Number of Wraps (W)

Suppose η is fixed while W changes but without affecting H_2. Further, recalling that the length of any section of the ultimate fancy yarn is the same along the fancy yarn axis, i.e. $L_1 = L_2 = \frac{1}{W}$; thus, an increase in the number of wraps W may reduce L_1. Besides that, and by referring to equation 4.16, an increase in W may reduce the length L_{e2} of one sigmoid section. Further, taking into consideration that in all types of helix L_{e2} >

H_2; so, the numerator in equation 4.27 is always greater in value than the denominator. Therefore, a change in the former is always more than a change in the latter. Consequently, n increases in value when W increases (i.e. if $\Delta W > 0$, then $\Delta n > 0$). Furthermore, regarding the sinusoidal parts, suppose H_1 is fixed and suppose the elliptical integration of the second kind, in equation 4.11, equals to ψ:

$$\psi = E\left(2\pi, \frac{4\pi^2 H_1^2 W^2}{4\pi^2 H_1^2 W^2 + 1}\right) \tag{4.29}$$

The value of this term can be estimated numerically when values of W and H_1 are available. However, to understand how it changes when only W changes, it was possible to assume that $4\pi^2 H_1^2 = 1$. Therefore,

$$\psi = E\left(2\pi, \frac{W^2}{W^2+1}\right) \tag{4.30}$$

Regarding the other part of equation 4.11, it was assumed that:

$$\mathcal{F} = \frac{\sqrt{2(4\pi^2 H_1^2 W^2 + 1)}}{2\sqrt{2}\,\pi\, W} \tag{4.31}$$

Where $\mathcal{F}$ can also be estimated numerically as shown in Table 18.

Table 18: The Relationship between the Number of Wraps and the Terms ψ and $\mathcal{F}$ of the Model

W (wrap per cm)	ψ	$\mathcal{F}$
1	5.20	10.00126
2	4.71	10.0003169
3	4.41	10.0001408
10	4.38	10.0000126
20	4.23	10.00000316

Considering the data of Table 18, it is found that when W increases, both ψ and $\mathcal{F}$ decrease. Eventually, when W increases, the length L_{e1} must decrease. If the height of such sinusoidal sections remains unchanged, but their length decreases, the width of their base L_1 must decrease. This means that their areas must decrease. Further, considering equation 4.28, when W increases without changing the height of the spiral sections, *m* decreases in value only if λ remains unchanged. In reality, however, the height H_2 of the already available helical or sigmoidal sections and the newly formed ones may increase slightly.

Since each wrap of the binder makes two sections, i.e. if W=1 thus λ =2. Therefore, a change in λ is twice any change in W, i.e. $\Delta\lambda = 2\Delta W$. For this, equation 4.28 can be rewritten as:

$$\Delta m = 2\Delta W - \frac{2\Delta W\, L_{e2}}{\sqrt{1+4\pi^2 \Delta W^2 \Delta H_2^2}} \tag{4.32}$$

The term $\frac{L_{e2}}{\sqrt{1+4\pi^2 \Delta W^2 \Delta H_2^2}}$ must be ≈ 1 to get $\Delta m \approx 0$. Therefore, the new length of the helically configured effect thread in one section of the fancy yarn must be approximately:

$$L_{e2} \approx \sqrt{1 + 4\pi^2 \Delta W^2 \Delta H_2^2} \quad (4.33)$$

4.7 Further Theoretical Advantages of the Model

Based on the equations of this modelling approach, it was possible to write an equation for the *Shape Factor of Fancy (Bouclé) Yarn* (ShF) which is introduced previously [4]. Recalling that the ShF= m × area under the length of the sinusoidal part L_{e1}; thus, when the technology used to make bouclé yarns does not involve the hollow-spindle system, the equation of ShF becomes:

$$\mathrm{ShF} = m \int_0^{L_1/2} H_1 sin\left(\frac{2\pi x}{L_1}\right) dx \quad (4.34)$$

so, $\mathrm{ShF} = m\,H_1[-\frac{\mathrm{L_1}}{2\pi}\cos\left(\frac{2\pi x}{L_1}\right)]_0^{L_1/2} = \frac{\mathrm{mH_1L_1}}{2\pi}(-cos\pi + cos0)$

or $\mathrm{ShF} = \frac{\mathrm{mH_1L_1}}{\pi}$ (4.35)

If, however, the hollow-spindle system is used, half the sine wave will be representing the bouclé profile which extends over L_1, and the equation becomes:

$$\mathrm{ShF} = m \int_0^{L_1} H_1 sin\left(\frac{2\pi x}{2L_1}\right) dx$$

so, $\mathrm{ShF} = m\,H_1[-\frac{\mathrm{L_1}}{\pi}\cos\left(\frac{\pi x}{L_1}\right)]_0^{L_1} = \frac{\mathrm{mH_1L_1}}{\pi}(-cos\pi + cos0)$

or $\mathrm{ShF} = \frac{\mathrm{2mH_1L_1}}{\pi}$ (4.36)

4.8 Further Practical Benefits of the Model in Industrial Situation

The implications of such a theoretical model in actual industrial situation are:

- to facilitate the manufacturing process of a copy of an already made fancy yarns if a previous knowledge about its manufacturing conditions is not available;

- to decide the type of multi-thread fancy yarn, after being made, based on the dimensions of its structures and components, i.e. H_2 , R_c ,R_e , *m*, *n*, λ, L_2; and
- to predict the structure and the appearance of multi-thread fancy yarns after modifying the number of wraps of the binder or the overfeed ratio of the effect component.

When designing a new fancy yarn from the beginning, the model can be used by:

- defining the technology used in order to decide the type of equation to be applied, i.e. whether the general form or the special form of the model;
- deciding the type of variant of fancy yarn to be made, i.e. bouclé, gimp, spiral, etc.
- choosing an overfeed ratio suitable to make such a type of fancy yarn;
- defining the number of wraps, to be used for the binder, taking into account the type of fancy yarn to be made and the overfeed ratio chosen. Information about these are given previously [24]. The structural Ratio of Fancy yarn is a useful tool to do so.
- deciding the machine settings and speeds of manufacturing;
- making the prototype of fancy yarn based on the previous conditions;
- testing the prototype to measure all its dimensions, in particular H_2 , H_1, R_c ,R_e , *m*, *n*;
- applying the equations of the model to manipulate the overfeed ratio and the number of wraps in order to improve the prototype or to make a specific structure of fancy yarn; and
- once the structure has been improved as intended, it is possible to start the full production of that specific type of multi-thread fancy yarn.

4.9 The Spinning Geometry of Multi-thread Fancy Yarn in the First Spinning Zone of the Hollow-spindle Machine

The spinning zone of the Gemmill & Dunsmore #3 hollow-spindle spinning machine may be divided into the following zone as shown in Figure 14:

- The First Spinning Zone (i.e. Zone 1) which is located between the supply rollers of the effect threads and the in-let hole of the hollow spindle;
- The Second Spinning Zone (i.e. Zone 2) which is located within the hollow-spindle between the in-let hole and the false-twist hook; and
- The Third Spinning Zone (i.e. Zone 3) which is located between the false-twist hook and the delivery rollers of the machine.

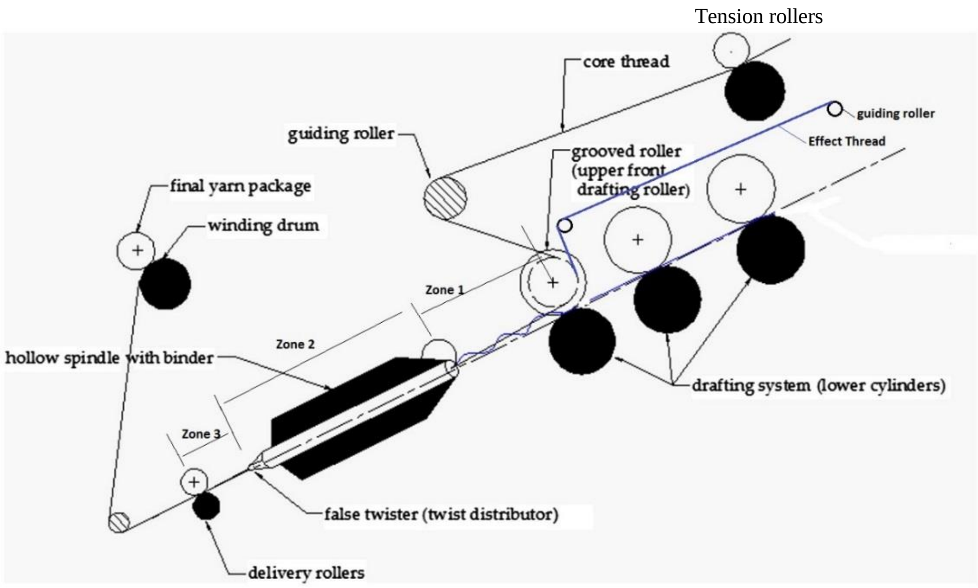


Figure 14: The Hollow-spindle Spinning Machine

4.9.1 Observational Approach

During the manufacture of multi-thread fancy yarns on the hollow-spindle spinning machine, it was observed that the effect thread formed a helical configuration around the core thread in the First Spinning Zone. Without such helical formation, it was not possible to make multi-thread fancy yarns. It was believed that the formation of the helices was partly induced and regulated by the false-twist hook. It was also thought that the nature of the helices may have correlated with the structure and quality of the ultimate multi-thread fancy yarn. Therefore, it was necessary to study the geometry of those effect-thread helices.

4.9.2 Importance of Studying the First Spinning Zone

Studying the First Spinning Zone was important for several reasons as follows:

- The effect thread must form a helical configuration around the core thread; otherwise, a multi-thread bouclé yarn cannot be made;
- The number of the helices formed and their radius may have a relationship with the size and number of bouclé profiles formed on the ultimate bouclé yarn. More helices are expected to result in more bouclé profiles. Additionally, wide helices are be expected to result in large bouclé profiles;
- Additionally, any fault occurring in the effect thread helices may have negative consequences on the structure of the final bouclé yarns. By way of example, the formation of loops, or at least one loop, from the effect thread, in the first spinning zone, may result in unusually large fancy loop profiles on the final bouclé yarn; and
- At excessive and unnecessary high rotational speeds it may become difficult to make a bouclé yarn, for specific value of the overfeed ratio, due to changes in the nature of helices in the First Spinning Zone. The fancy yarns which result may be gimp yarns, wavy yarns or overfed fancy yarns. One solution to this situation may be to increase the overfeed ratio. However, doing so will result in heavier bouclé yarns and increases the cost of production. It might also affect the quality of the product negatively. However, the bouclé yarn manufacturer needs to strike balance

between costs, quality and specifications of the bouclé yarns. Such a balance may be achieved through controlling the spinning geometry in the First Spinning Zone.

The geometry of the intermediate product, which is made as a first step for making the final bouclé yarn, is decided in the First Spinning Zone. Some of the changes happing later to this geometry are known and they are summarised as follows [24, 37]:

- The binder joins the effect thread and the core thread in the Second Spinning Zone;
- False-twist is imparted to the intermediate product in the Second Spinning Zone within the hollow spindle, i.e. upstream of the false-twist hook; and
- The false twist is removed in the Third Spinning Zone, i.e. downstream of the false-twist hook.

4.9.3 Mathematical Approach

The triangle resulting from unwrapping only one helix of the effect thread is presented in Figure 15. In theory, a helix of the effect thread may be obtained at a suitable value of rotational speed of the hollow-spindle. If the rotational speed is raised sufficiently, more helices may be formed for the same length of the effect thread. However, the radius of the helices will become narrower. Mathematically, the helix angle ($\beta=\beta_R=\beta_r$) is not expected to change as indicated in Figure 16.

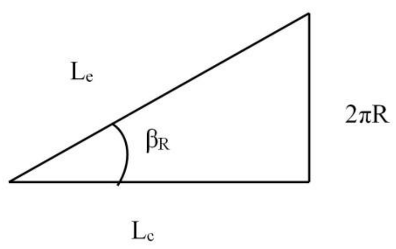


Figure 15: A Triangle of One Helices in the First Spinning Zone

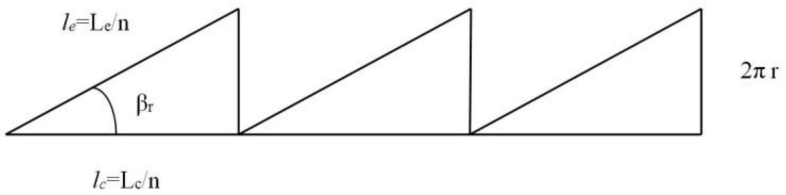


Figure 16: Triangle of Several Helices of the Effect Thread

For only one helix (Figure 15), the length of the effect thread L_e in relation to the length of the core thread L_c and the radius of the helix R was given by *Pythagoras* formula as:

$$L_e = \sqrt{(2\pi R)^2 + L_c^2} \tag{4.37}$$

If n identical helices of r radius were formed (Figure 16), while L_e and L_c remain unchanged, the length of the effect thread and the core thread for each new helix may become l_e and l_c respectively, such that:

$$\mathrm{L_e} = \mathrm{n}\, l_e \quad \text{and} \quad \mathrm{L_c} = \mathrm{n}\, l_c \tag{4.38}$$

The length l_e was also given by *Pythagoras* formula as follows:

$$l_e = \sqrt{(2\pi r)^2 + l_c^2} \tag{4.39}$$

Re-arranging equation (4.39) and substituting equation (4.38) in it resulted in:

$$(\frac{\mathrm{L_e}}{\mathrm{n}})^2 = (2\pi r)^2 + (\frac{\mathrm{L_c}}{\mathrm{n}})^2 \tag{4.40}$$

After rearranging such a relationship, the following equation obtained:

$$(2\mathrm{n}\pi r)^2 = \mathrm{L_e^2} - \mathrm{L_c^2} \qquad (4.40)$$

However, it was shown in equation (4.18) that the overfeed ratio of the effect thread was:

$$\eta = \frac{\mathrm{L_e}}{\mathrm{L_c}} \tag{4.41}$$

Suppose that the helix angle was β; thus:

$$\cos\beta = \frac{1}{\eta} \tag{4.42}$$

Eventually, the equation (4.40) became:

$$(2n\pi r)^2 = \eta^2 L_c^2 - L_c^2 = L_c^2(\eta^2 - 1) \tag{4.43}$$

or

$$r = \frac{L_c\sqrt{\eta^2 - 1}}{2\pi n} \tag{4.42}$$

Equation (4.42) accounts for one important dimension of the helices formed, which are their radius. Counting the number of the helices and having a knowledge about both the overfeed ratio and the length of the core thread in the First Spinning Zone may suffice to estimate the radius of the effect-thread helices. It was assumed that the core thread remains straight while making the fancy yarns; thus, the core thread had the same length as the First Spinning Zone.

4.9.4 Nomenclature for the Model of the First Spinning Zone

n is number of the effect-thread helices in the First Spinning Zone.

β is angle of the effect-thread helix if only such a helix forms in the First Spinning Zone.

R is radius of one helix if only such a helix forms in the First Spinning Zone.

r is radius of several helices.

l_e is length of the effect thread in one helix amongst several identical helices in the First Spinning Zone.

l_c is length of the core thread in one helix amongst several identical helices in the First Spinning Zone.

L_c is length of the core thread required to make only one helix in the First Spinning Zone

L_e is length of the effect thread required to make only one helix in the First Spinning Zone

4.10 Conclusions of the Modelling Approach

The modelling approach of this research was related to the mathematical modelling of the structure of multi-thread fancy yarns by taking into account the length of the effect thread(s), the number of wraps and the overfeed ratio. Such a structure was first modelled graphically and examined visually. It was considered to have two parts-sinusoidal and helical. An incomplete elliptic integral of the second kind was used to calculate the length of the effect thread in the sinusoidal part, while simple trigonometry equations were used to account for the spiral sections of the effect thread. This mathematical model was universal for doubled fancy yarns, because it accounts for several types of fancy yarn ranging from a “pure” bouclé yarn to bouclé yarn, semi-bouclé yarn, overfed fancy yarn, gimp yarn or its derivates, and a spiral yarn. Further, it was simpler than the previous versions which were reported in Section 2.13. Furthermore, this mathematical model was believed to be easy to apply in industry, to estimate the structure of a multi-thread fancy yarn, and in academia, for further development. Moreover, based on the same model, the Shape Factor of Fancy (Bouclé) Yarn, which was used to assess the Absolute Fancy Bulkiness of Bouclé Profiles, was also modelled using simple mathematical formula.

The modelling approach of this study was further extended to account for the First Spinning Zone of the hollow-spindle machine. A number of helices formed from the effect thread around the core thread in this zone. The dimensions and number of the helices may have an impact on the quality parameters and the structural parameters of multi-thread fancy yarns, including bouclé yarns. Therefore, a simple mathematical model (i.e. equation) was presented to account for the radius of the helices. This model indicated that the value of radius r is related to the number of the helices formed, the overfeed ratio η of the effect thread and the length of the core thread in the First Spinning Zone.

Chapter 5: Experimental Studies: Results and Discussions

5.1 Testing the Geometrical Model of Multi-thread Bouclé Yarn Made on Hollow-spindle Spinning Machines

The experimental procedures to test the geometrical model of multi-thread fancy yarn are given in Section 3.4. The yarns made for this purpose are shown in Figure 17. This figure shows that those fancy yarns are different from each other in particular the geometry, thickness, type and shape of the fancy profiles, and less importantly, the colour. Those fancy yarns may be classified as follows:

- yarns 1, 3, and 6 may be regarded as examples of gimp yarn.
- yarns 2, 13, and 15 may be regarded as examples of semi-bouclé yarn.
- yarns 4, 5, 7, 8, 9, 11, 12 may be regarded as examples of bouclé yarn.
- yarn 10 may be regarded as an example semi-loop yarn.
- yarn 14 may be regarded as an example of wavy yarn.

Due to the aforementioned differences, those fancy yarns were suitable to test the versatility of the geometrical model as a universal geometrical model for doubled fancy yarn.

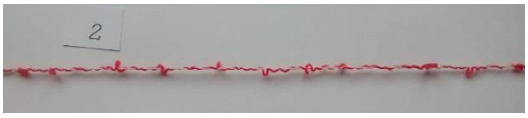
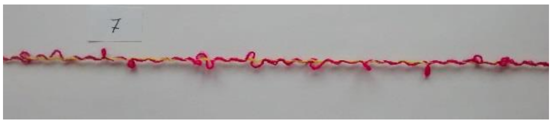
gimp yarn  	semi-bouclé yarn 
gimp yarn  	bouclé yarn 
bouclé yarn  	gimp yarn 
bouclé yarn  	bouclé yarn 
bouclé yarn  	semi-loop yarn 
bouclé yarn  	bouclé yarn 
semi-bouclé yarn  	wavy yarn 
semi-bouclé yarn  	

Figure 17: Images of the Fancy Yarns Used to Test the Geometrical Model of Multi-thread Fancy Yarn

The numerical results are given in Table 19.

Table 19: Results of Testing the Geometrical Model of Multi-thread Fancy Yarn Made on a Hollow-spindle Spinning Machine

Fancy Yarn	**n per dm**	**m per dm**	**W per dm**	**H2 mm**	**H1 mm**	**Predicted Value of Le , (P) mm**	**Actual Value of Le , (A) mm**	**Deviation from Predicted Value, (A-P) mm**	**Percentage Deviation from Predicted Value, (A-P/P) × 100%**
Fancy yarn 1	11	6	17	1.10	2.66	15.3	14.5	-0.8	-5.23
Fancy yarn 2	17	11	28	0.65	1.87	16.6	16.6	0	0.00
Fancy yarn 3	24	6	30	0.71	2.79	17.1	16.7	-0.4	-2.34
Fancy yarn 4	9.5	10	19.5	0.55	3.67	21	18.5	-2.5	-11.90
Fancy yarn 5	17	10	27	0.62	2.48	17.9	16.7	-1.2	-6.70
Fancy yarn 6	9	23	31	0.72	1.48	19.7	16.9	-2.8	-14.21
Fancy yarn 7	10.5	9	19.5	0.97	3.73	21.0	17.07	-3.93	-18.71
Fancy yarn 8	10.5	6	16.5	0.71	3.74	16.8	15.63	-1.17	-6.96
Fancy yarn 9	15	6	21.0	0.69	3.95	18.1	16.80	-1.3	-7.18
Fancy yarn 10	13	9	22.0	0.57	3.32	19.4	16.77	-2.63	-13.56
Fancy yarn 11	15	7	22.0	0.60	4.40	20.5	15.40	-5.1	-24.88
Fancy yarn 12	1.2	8	20.0	0.57	3.81	19.6	16.47	-3.13	-15.97
Fancy yarn 13	22	3	25.0	0.49	2.46	12.9	12.80	-0.1	-0.78
Fancy yarn 14	20	0	20.0	0.60	0.00	10.9	11.03	0.13	1.19
Fancy yarn 15	18.5	3	21.5	0.61	2.27	12.6	12.87	0.27	2.14

It was found that the *correlation coefficient* was (r) =0.90 between the theoretical values and the experimental values of L_e. Not only it was a high value of r, but it also was significant at a significance level α=0.01 (and the p-value of the ANOVA testing was 0.000). The deviation between the theoretical values and the actual values was in the range -24.88 and 2.14%. This deviation was as follows: 3 yarns had deviation between 2.14 and 0 %. Six yarns had deviation between -0.78 and -7.18 %. Further five yarns had deviation between -11.9 and -18.71 % while one yarn had a deviation of -24.88 %. Due to the nature of the fancy yarn structure, which is based on deliberate variability, it is not uncommon to obtain values of deviation as high as 15% [34, 35]. However, the last value of deviation of -24.88% was high. This deviation may have resulted because some of the bouclé profiles of this yarn were elongated instead of having the shape of a short sine wave having wide amplitude.

The difference between the experimental values and the expected values may have resulted due to several reasons. These may include the helical configuration of the core thread (which was assumed to be straight in the model), the variation in the manufacturing process and random variation. In all cases, the value of r was high, which shows the applicability of the model. Therefore, it was possible to use the model to predict the length of the effect thread and the overfeed ratio necessary to make a particular multi-thread fancy yarn when the technology required to make it was already known. It was only required to analyse the structure of fancy yarn by counting the number of the effect profiles, measuring their dimensions, then use the model to get a statistically significant estimation of the length of the effect thread and the overfeed ratio required to make such a fancy yarn.

5.2 Results of Reverse-engineering the Fancy Yarns based on the Results of the Geometrical Model of Multi-thread Fancy Yarn

Figure 18 shows images of the copies of the fancy yarns 9, 12, 13, 14 and 15.

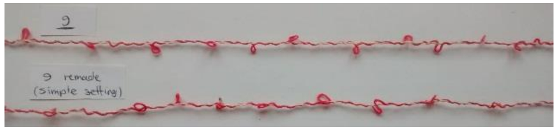
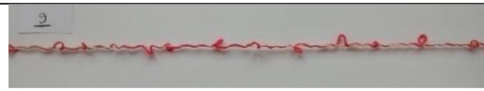
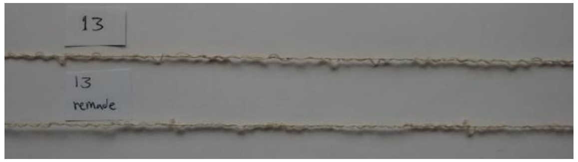
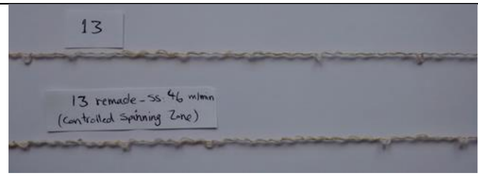
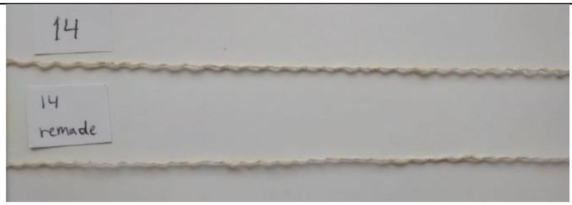
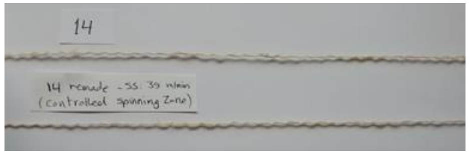
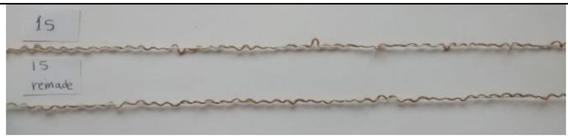
Comparison with the first copies of the yarns	**Comparison with the second copies of the yarns**
	 
	No need to make a second copy of yarn 12
	
	
	No need to make a second copy of yarn 15

Figure 18: Comparison between the Original Fancy Yarns and their Copies that are Made Based on the Geometrical Model of Multi-thread Fancy Yarn

The copies of yarns 12 and 15 resembled the original yarns. However, the copies of yarns 9, 13 and 14 did not appear to resemble the original yarns. This is because the copy of yarn 14 was thinner than the original yarn. Further, the copy of yarn 13 had lower number of bouclé profiles in comparison with the original yarn. Moreover, the first copy of yarn 9 had lower number of larger bouclé profiles in comparison with the original yarn. However, this problem was solved by controlling the First Spinning Zone and the solution was applied to fancy yarns 9, 13 and 14.

By controlling the First Spinning Zone when making the second copy of yarns 9, 13 and 14 the core thread was allowed to form a regular balloon in the First Spinning Zone and the effect thread made regular helices around the core thread. So, the second copies of yarns 9, 13 and 14 appeared to resemble the original fancy yarns. A similar approach may be applied to reverse-engineer the fancy yarns 1 ~ 15.

5.3 Exploring the Influence of the Overfeed Ratio on the First Spinning Zone

The experimental procedures are given in Section 3.5 while the material used and the machine settings are given in Section 3.6.1. Table 20 gives the results of this experiment and the expected values of radius r, while Figure 19 shows images of the First Spinning Zone corresponding to the overfeed ratio of each machine setting.

Table 20: Influence of Only the Overfeed Ratio on the First Spinning Zone

Setting Number	Number of Helices Formed	Theoretical Value of Radius of Helices; mm	Comments on the First Spinning Zone
1	4	1.05	The helix was touching the core thread
2	4	1.32	The helix started to separate from the core thread
3	4	1.56	Regular helices
4	4	1.78	Regular helices
5	3	2.12	A loop has formed
6	4	2.18	A loop has formed with a wider diameter than previously
7	3	3.17	Helices have formed with a loop
8	4	2.57	A loop has formed with a wider diameter than the previous setting
9	3, 3.5 or 4	3.15	A loop has formed with a wider diameter than the previous setting
10	3, 3.5 or 4	3.35	A loop has formed with a wider diameter than the previous setting
11	3, 3.5 or 4	3.56	A loop has formed with a wider diameter than the previous setting

Figure 19: Images of the Spinning Geometry when the Influence of Only the Overfeed Ratio on the First Spinning Zone was Tested

Table 20 indicates that the number of helices was 3 or 4 and in some occasions it was 3.5. So, the change which happened to this number was only variation. Therefore, the overfeed ratio did not affect the number of the helices n. However, the radius of the helices increased with the overfeed ratio. Further, it was observed that excessive overfeed ratios resulted in the formation of loops from the effect thread in the First Spinning Zone. Moreover, it was observed that the size of those loops increased with increasing the overfeed ratio. In this experiment, the minimum overfeed ratio that was used and made helices with a loop was $\eta=1.6$. Overfeed ratios higher than that created irregular fancy profiles on the resultant fancy yarn.

Since the number of the helices formed did not change, except due to variation, it was concluded that it may be related to a different factor, such as the rotational speeds. Further, the variation in the number of the helices may have resulted due to the variations in the input materials and the variation of the machine. Furthermore, it was observed that defects in the effect thread, in particular thick places and slubs, contributed to the formation of loops. It was also observed that those loops led to the formation of defects on the bouclé yarn structure such as large loops or large unstable fancy profiles.

5.3.1 Conclusions

- The overfeed ratio did not have an influence on the number of the effect-thread helices, but increasing the overfeed ratio increased the radius of the helices, and vice versa.
- Further, observing the overfeed ratio gave an indication about the suitability of the overfeed ratio to the speeds of the machine, i.e. excessive overfeed ratios resulted in the formation of loops (from the effect thread) alongside the helices.
- Moreover, the number of the helices may be related to a different factor, such as the rotational speeds.

5.4 Testing the Influence of the Rotational Speed on the First Spinning Zone when the Number of Wraps are Changed

The experimental procedures are given in Section 3.5 while material used and the machine settings are given in Section 3.6.2. Figure 20 shows images of the First Spinning Zone related to this experiment.

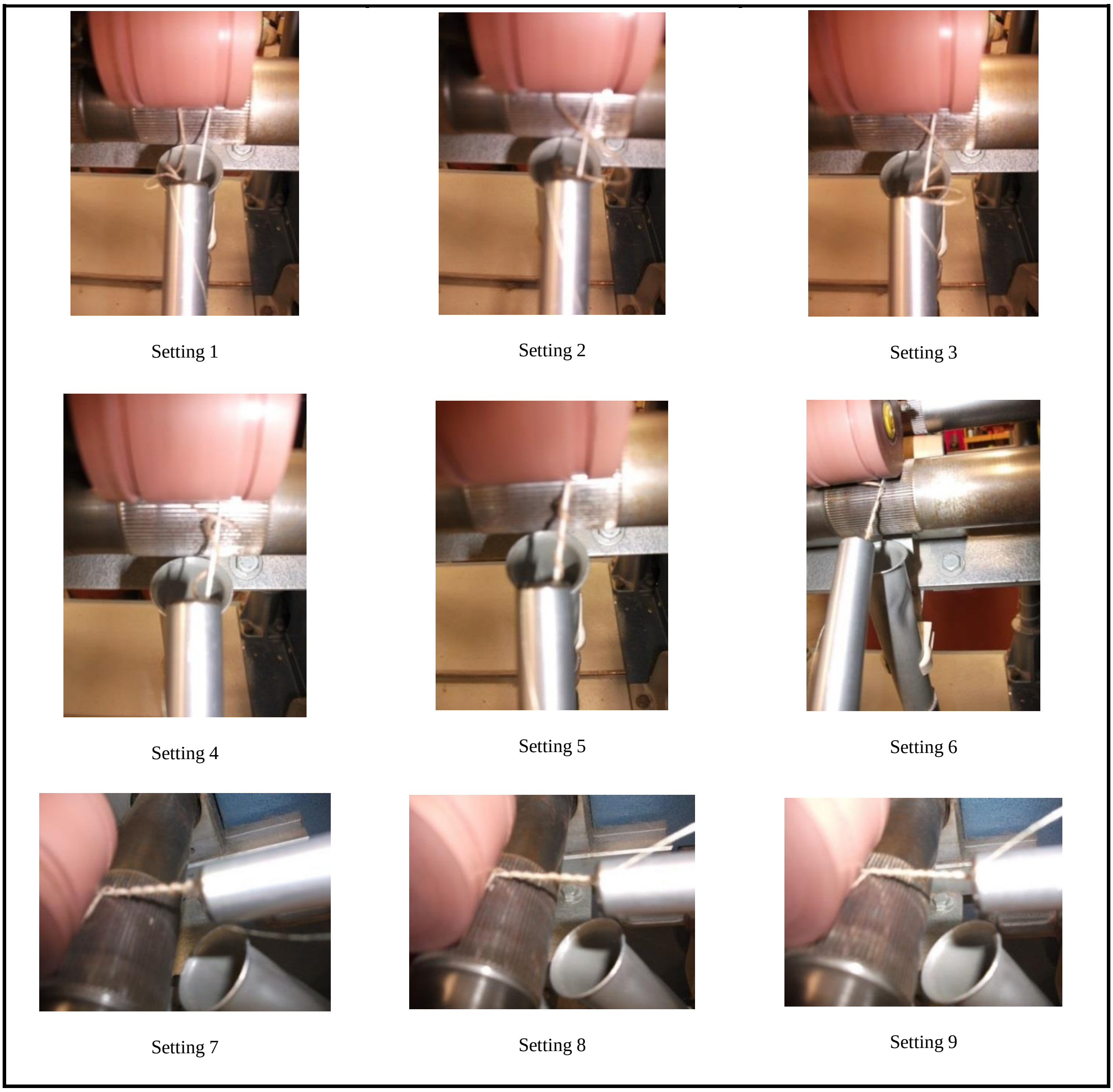


Figure 20: Images of the Geometry of the First Spinning Zone when the Rotational speed and Number of Wraps were Changed

Figure 20 shows that settings 1, and 2 of the machine were not able to make any helix from the effect thread in the First Spinning Zone. However, helices stated to form when the machine was set at settings 3, 4, 5, 6, 7, 8, and 9. The helices made at settings 3 and 4 appear to be extremely wide and irregular. However, starting from setting 5, more regular helices were formed. The detailed observations related to the First Spinning Zone are reported in Table 21 which gives the results of this experiment for each machine settings.

Table 21: the Results of Observing the First Spinning Zone when the Rotational speed and Number of Wraps were Changed

Setting Number	Number of Helices Formed	Comments on the First Spinning Zone
1	0	No helices have formed because the buckling of the effect thread was not complete nor regular
2	1	The helix was irregular and was affected by the gravitational force
3	1 or 2	There were some irregularity and deformations in the helix at the inlet of the hollow spindle
4	2	There were some irregularity and deformations in the helix at the inlet of the hollow spindle
5	2.5, 3 or 3.5	Irregularity of the number of helices by time was observed; perhaps because of vibration of the machine parts.
6	4.5 or 5.5	Regular helices have formed with narrower diameters than setting 5
7	7 or 8	Regular helices have formed with narrower diameters than setting 6
8	8 or 9	Regular helices have formed with narrower diameters than setting 7
9	9 or 10	Regular helices have formed with narrower diameters than setting 8

It was observed that increasing the rotational speed of the hollow spindle resulted in a corresponding increase in the number of the helices (*n*). However, the overfeed ratio did not contribute to the number of the helices when both the rotational speed and the number of wraps were changed. Further, the diameters of the helices became narrow when the number of the helices increased. Furthermore, taking into account the effect threads used, the minimum rotational speed which was not suitable to make a fancy yarn was RS= 5000 rpm because it failed to make helices. However, regular helices were formed when the rotational speed was RS≥6000 rpm. The reason for this could be the decrease in the diameter of the helices which became relatively narrow by increasing the rotational speed. Therefore, it was confirmed that the number of the helices formed was related to the rotational speed. By taking into account the average number of helices corresponding to each machine setting, it was found that the Pearson coefficient of correlation between the rotational speed and the number of helices was 0.977. This value was significant at the significance level $\alpha=0.05$ because the p-value = 0.000.

5.4.1 Conclusions

When the number of the wraps was left to change according to the changes in the rotational speed, the number of the effect-thread helices was proportional to the rotational speed.

5.5 Testing the Influence of the Rotational Speed on the First Spinning Zone and the Bouclé Yarn Structure when the Overfeed Ratio and the Number of Wraps are Fixed

This experiment completed the previous investigation reported in Sections 5.3 and 5.4 related to the First Spinning Zone. The experimental procedures are given in Section 3.5 while material used and the machine settings are given in Section 3.6.3. The observations related to the First Spinning Zone are reported in Table 22 while the fancy yarns made are shown in Figure 21.

Table 22: Observations Related to the Influence of Only the Rotational Speed on the First Spinning Zone

Setting Number	Theoretical Value of Helix Radius mm	Observations on the First Spinning Zone	Fancy Yarn
1	2.81 mm or 2.41 mm	The number of helices formed was 3, or 3.5 and there was loop formation.	yarn 1
2	2.81 mm or 2.11 mm	3 or 4 helices have formed with loop (s).	yarn 2
3	2.11 mm or 1.68 mm	4 or 5 helices were formed. No ballooning of the core thread. When alteration in the number of helices happened, momentary, the helix configuration became unbalanced and a loop has formed.	yarn 3
4	1.68 mm , 1.40 mm or 1.20 mm	There was weak wobbling of the core thread, rather than ballooning. The helices formed were 5, 6 or 7. There were several breakages of the core thread.	yarn 4
5	Not clear	The number of helices was not clear due to ballooning of the core thread; ballooning resulted because of the high rotational speed used.	yarn 5

Due to the technical capabilities of the microscope used, Figure 21 shows 2D photos of the 3D structures of the fancy yarns over only short lengths of the fancy yarns. However, it was sufficient to reflect the differences in the geometry of the five fancy yarns made. For example, Figure 21 shows that nature of the structure was similar for yarns 1 and 2. Such a structure had a minority of large bouclé profiles while the other sections were sigmoidal. When making the fancy yarns from 2 until 5, the bouclé profiles became smaller. Further, their number was increasing on the expense of the sigmoidal sections. Furthermore, a few sigmoidal sections became wider, i.e. became wavy parts. When reaching yarn 5, the structure had only bouclé profiles, a few wavy profiles but no sigmoidal sections.

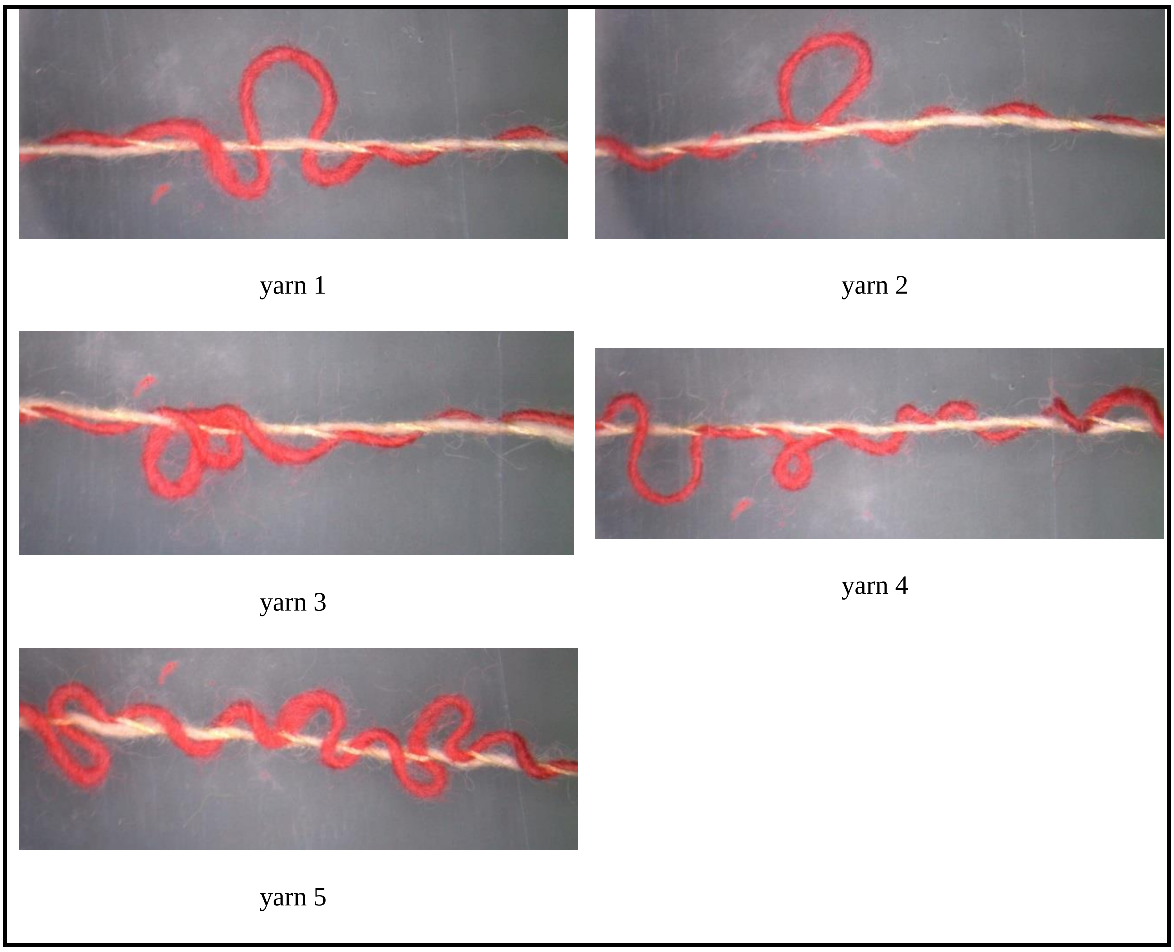


Figure 21: Images of the Fancy Yarns When Testing the Influence of Only the Rotational Speed on the First Spinning Zone

The numerical results of the testing procedures are given in Table 23.

Table 23: Numerical Results When Testing the Influence of Only the Rotational Speed on the First Spinning Zone

Fancy Yarn	Number of Helices	Size of Fancy Profile mm^2	SD of Size mm^2	Circularity Ratio of Fancy Profile %	SD of Circularity %	Number of Fancy Profiles dm^{-1}	SD of Number dm^{-1}	ShF of Fancy Yarn mm^2 dm^{-1}
Yarn 1	3 or 3.5	24.13	10.14	53.68	15.43	4.88	1.29	117.75
Yarn 2	3 or 4	20.61	8.51	60.67	20.17	5.46	1.18	112.53
Yarn 3	4 o 5	18.96	10.24	54.48	21.83	6.06	0.96	114.89
Yarn 4	6 or 7 or 5	9.97	2.04	62.12	15.7	8.33	2.4	83.05
Yarn 5	not clear	11.68	5.87	65.26	16.06	9.8	1.9	114.46

The data of Table 23 related to the average size of the fancy profiles and their number were depicted visually in Figure 22 and Figure 23 respectively.

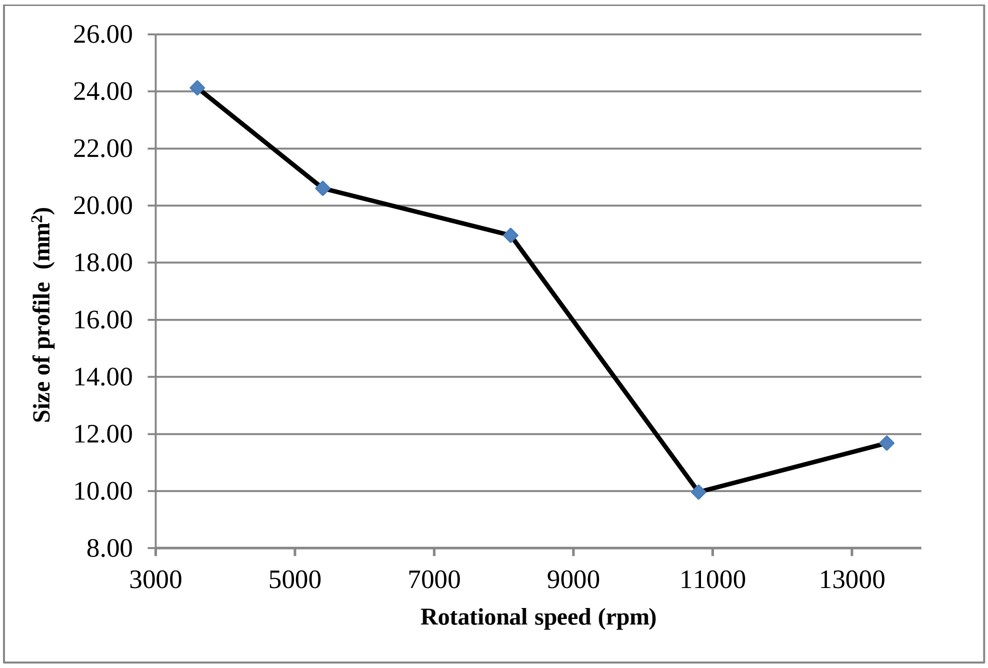


Figure 22: Relationship between the Size of Fancy Profile the Rotational Speed in Experiment 3

It is shown from Figure 22 that the size of fancy profiles decreased by increasing the rotational speed. Further, when RS became higher than a certain level (i.e. 9000 rpm), the profiles became extremely small, e.g. yarns 4 and 5. Furthermore, the number of large fancy profiles over those yarns was as low as 4.88 ~ 6.06 per dm. Additionally, Figure 23 shows that the small fancy profiles of yarns 4 and 5 were more in number than the case of the other fancy profiles and reached about 9.8 profiles per dm. Moreover, the average Circularity Ratio of Fancy Profile (CR) was highest for fancy yarns 4 and 5; the circularity ratio was 62.12 and 65.26 respectively. Therefore, as shown in previous studies [4, 28], the value of CR indicated that yarns 4 and 5 had better bouclé profiles than yarns 1, 2 and 3.

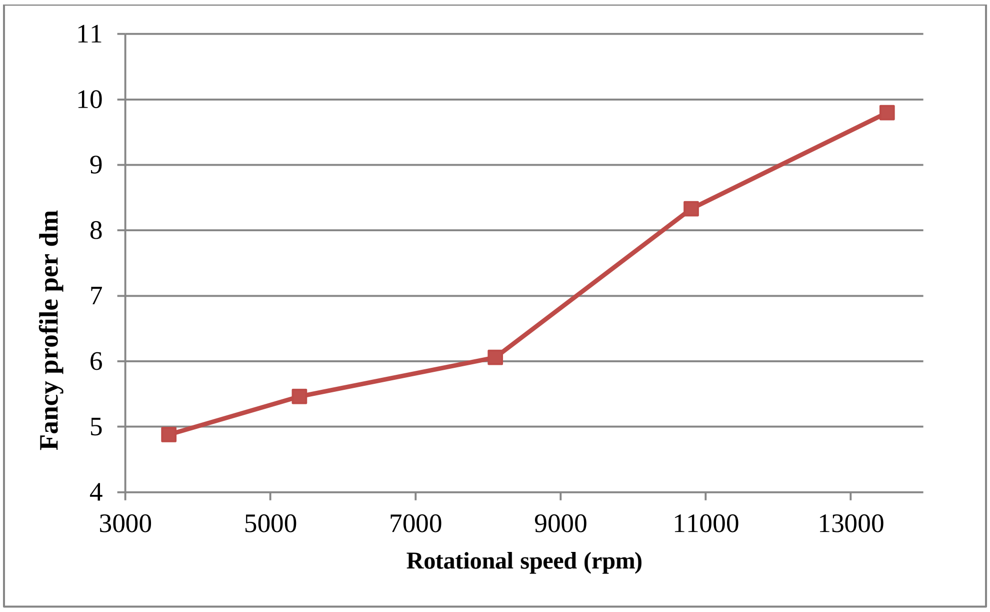


Figure 23: Relationship between the Number of Fancy Profiles and the Rotational Speed in Experiment

The relationships shown in Figure 22 and Figure 23 represented regression models as follows:

$$\text{Size of fancy profile (mm}^2) = 28.7 - 0.00140\ \text{RS} \tag{5.1}$$

$$\text{Number of fancy profiles (per dm)} = 2.69 + 0.000509\ \text{RS} \tag{5.2}$$

The statistical studies of these two regression models are given in Table 24.

Table 24: Statistical Study of Regression Models Reported When Testing the Influence of Only the Rotational Speed on the First Spinning Zone

Regression Model of	Predictor	Coefficient	P-value of t-test	Accuracy of Regression Line	P-value of ANOVA Test
Size of Bouclé Profile	**Constant**	28.693	0.002	SE= 2.557 R^2 = 86.5% R^2 (adj)= 82.0%	0.022
	RS	-0.0014	0.022		
Number of Bouclé Profiles	**Constant**	2.6908	0.018	SE= 0.507 R^2 = 95.5% R^2 (adj)=94.1 %	0.004
	RS	0.0005	0.004		

It is confirmed that both regression models were significant at a significance level α=0.05 as inferred from the p-values of Analysis of Variance (ANOVA). Additionally, all terms included in the models were significant at α=0.05 because all p-values of t-tests were smaller than α=0.05. Further, the accuracy of the fitted lines of the models was high since the values of *Coefficient of Determination* R^2 were high (i.e. 86.5 % and 95.5 % respectively). However, the second model was more accurate than the first one because the value of adjusted R^2 was higher than that of the first regression model (i.e. 94.1 % ≥ 82.0%).

It is shown from the data of Table 23 and Figure 21 that the bouclé yarns made were different in appearance, texture and quality, although all those fancy yarns had identical values of input thread thickness, number of wraps and the overfeed ratio. In particular, the average size of the bouclé profiles for yarns 1, 2 and 3 was excessively large and it was in the range of 15.02 ~ 20.61 mm^2. Those differences were related to the spinning geometry in the First Spinning Zone, where the effect thread formed several helices around the core thread. A few wide helices resulted in a low number of large fancy profile along the fancy yarn axis. However, when the helical configuration had a narrow diameter and more helices, a high number of small fancy profiles has resulted. The number of helices was low in the case of yarns 1, 2, and 3, due to the low values of rotational speed. Further, due to the fixed overfeed ratio, the diameters of such helices were wider than that in the cases of the higher rotational speeds for yarns 4 and 5. However, when the rotational speed was sufficiently high, for yarns 4 and 5, the values of radius of the helices became lower. Additionally, because of the fixed overfeed ratio, the number of helices formed was higher than before.

It was observed that the stability of the helices determined the consistency of the ultimate fancy yarn structure; any deformation in the helical configuration had an impact on the fancy profiles. When a loop was formed in the First Spinning Zone, it was fixed later by the binder into the fancy yarn structure and appeared as a closed, large loop on the fancy yarn. Generally speaking, such loops were not desirable when making the bouclé yarns because they usually result in circular loops instead of bouclé profiles. However, loops are suitable for a loop yarn with circular profiles. In all cases, the main reasons for the helix deformation may have been:

(1) the variability of the effect-thread characteristics, i.e. linear density, bending stiffness, short-term faults, shape of the cross-section, etc.
(2) the vibration in the machine parts;
(3) deformation in the supply rollers; and
(4) the variability in pressure imposed on the supply rollers.

Loops, which may result in circular profiles are suitable for only loop yarns, have formed in the cases of yarns 1, 2, and 3 and appeared over the fancy yarns' surfaces. Further, almost a periodical alteration to the number of helices was observed when making those fancy yarns. During such changes in the number of helices, a loop or more loops have formed. Those loops found a place over the surface of the resultant fancy yarns.

It was observed that the core thread of yarn 5 had ballooned when making this fancy yarn. The reason for this was mainly due to the high rotational speed. Such ballooning had a positive influence on the fancy yarn structure, but it made it difficult to count the number of helices of the effect thread.

5.5.1 Subjective Assessments of the Fancy Yarns

Images of the yarns are shown in Figure 21. By assessing the fancy yarns from yarn 1 to yarn 5, it was found that the structure of the yarns improved and became more desirable. Furthermore, the size of the fancy projections of those yarns became more regular and closer to semi-bouclé profiles and bouclé profiles. Additionally, the difference in size between the fancy profiles and the sigmoidal sections became less visible, starting from fancy yarn 1 until fancy yarn 5.

Fancy yarn 1 had a few bouclé and semi-bouclé profiles and a few fancy waves or arcs while the sigmoidal sections were narrow. Some of the semi-bouclé profiles were closed projections. It was found that the size of the bouclé projections was extremely large in relation to the width of the sigmoidal sections.

Fancy yarn 2 had a higher number of smaller fancy profiles in comparison with yarn 1. Further, the fancy waves were more (in number) and larger (in size) than those of yarn 1. However, the sigmoidal sections were as narrow as yarn 1. The majority of the fancy profiles of yarn 2 were bouclé and some of them were closed or with crossed “legs”, i.e. similar to deformed circles or ellipses. Further, some of the semi-bouclé projections were clustered in pairs or as three projections together. The difference in size between the bouclé profiles and the other sections (i.e. the background) was smaller than yarn 1.

With regard to fancy yarn 3, this yarn had a higher number of smaller fancy profiles than yarn 2. Further, the number of wavy sections and arcs was higher than yarn 1 and yarn 2. Moreover, the sigmoidal sections were wider and shorter, but with higher variability in their lengths, than yarn 1 and yarn 2. Yarn 3 also had some clustered semi-bouclé projections (similar to the case of yarn 2). Some of the semi-bouclé projections had crossed legs or were closed, i.e. similar to ellipses. The differences in size between the various sections of the yarn were lower than yarn 1 and yarn 2.

Fancy yarn 4 had a higher number of smaller fancy profiles than yarns 1, 2 and 3. Although some clusters were observed on this yarn, their number was smaller than yarns 1, 2 and 3. The majority of the fancy profiles were bouclé and some of them were flexed bouclé projections. The yarn structure also had sigmoid, arcs and wavy sections. Since the majority of the fancy profiles were bouclé profiles, this meant that the structure of this fancy yarn was more desirable than the previous yarns.

Finally, it was observed that there was an increase in the number of fancy projections on yarn 5. The size of those profiles was smaller than all previous yarns. Large fancy profiles were rare on this yarn while the lengths of the sigmoidal sections along the axis of this yarn were variable.

5.5.2 Conclusions

When both the number of wraps and the overfeed ratio were fixed, the number of effect-thread helices increased with the rotational speed of the hollow-spindle. Additionally, the number of bouclé profiles increased while their average size decreased. Therefore, the fancy yarns made at different rotational speeds were different in structure, appearance and the quality parameters.

5.6 Testing the Influence of the Rotational Speed, Thickness and Stiffness of the Effect Thread on the Structure of Bouclé Yarn

The experimental procedures are given in Section 3.5 while the material used and the machine settings are given in Section 3.6.4. The observations about the First Spinning Zone are shown in Table 25. One important observation was the inability of both effect threads, the thin and the thick, to make fancy yarns at setting 1 of the machine. Another important observation was the inability of the thinner, softer effect thread to make a fancy yarn at the second the machine setting. Further, there were alterations to the number of the effect-thread helices. The reasons for this may have been variation in the input material, variation originating from the machine and random variation.

Table 25: Observations about the First Spinning Zone When Testing the Influence of the Rotational Speed and Thickness of the Effect Thread on the Structure of Bouclé Yarn

Machine Settings	Group I : Lambswool 83 tex B=0.711 g mm^2		Group II : Wool R118/2 tex B=4.20 g mm^2	
	Number of Helices in 40 mm	**Observations on the First Spinning Zone**	**Number of Helices in 40 mm**	**Observations on the First Spinning Zone**
1	0	No regular formation of helices- no fancy yarns	0	No regular formation of helices- no fancy yarns
2	0	No regular formation of helices- no fancy yarns	4 or 4.5	Regular helices
3	3 or 4	Formation of large loops	6 or 6.5	Regular helices and slight wobbling of the core thread
4	7	Wobbling of the core thread- narrower helices	8 or 8.5	Regular helices and slight wobbling of the core thread
5	9	Wobbling of the core thread	9; 9.5 or 10	Wobbling or ballooning of the core thread
6	Not totally clear due to high RS, but approximated to 10	Wobbling of the core thread	Not totally clear due to high RS, but approximated to 9.5	Ballooning of the core thread

The fancy yarns made are shown in Figure 24. Due to the technical capabilities of the microscope used, this figure shows only short lengths of the fancy yarns made. Additionally, it shows 2D photos of 3D structures of the fancy yarns. However, it reflected the differences between the two groups of fancy yarn and amongst the fancy yarns of each group. It is shown that as the machine setting was changed from setting 2 until setting 6, the fancy profiles of the two groups of fancy yarn became decreasing for both group of fancy yarn. Further, the number of the wavy profiles increases at the expense of the sigmoidal sections. Furthermore, the profiles of Group II of fancy yarn appeared to be larger than those of Group I of fancy yarn.

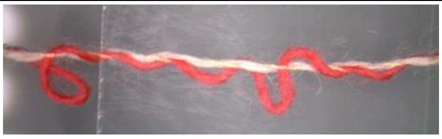
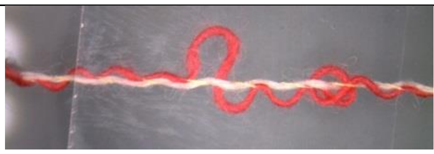
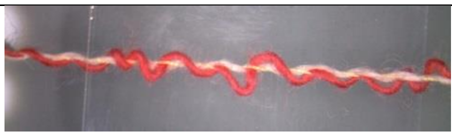
Machine setting	Group I	Group II
2		 Yarn 2
3	 Yarn 3	 Yarn 3
4	 Yarn 4	 Yarn 4
5	 Yarn 5	 Yarn 5
6	 Yarn 6	 Yarn 6

Figure 24: Images of the Fancy Yarns of the Two Groups of Effect Threads

The fancy yarn of settings 4 and 5 were bouclé yarns and those of setting 6 were semi-bouclé yarns. Setting 2 was capable of making a fancy yarn only when using the thick two-ply wool effect thread (R118/2 tex). The thinner, softer effect thread resulted in clustered bouclé profiles when using the second setting of the machine.

These yarns were tested objectively according to the method reported in Section 3.1.1. The results of this objective assessment are given in Table 26. The data of this table were used to plot line charts in Figure 25, Figure 26 and Figure 27. It was observed that the number of wraps used to make fancy yarn 6 using the thick effect thread made a compact fancy yarn. The wraps for this fancy yarn were excessive in relation to its structure.

Table 26: Qualities of the Bouclé Yarns Made for this Experiment

Machine Setting	Number of Helices in the First Spinning Zone (40 mm)		Mean (and SD) Size of Bouclé Profile, mm^2		Mean (and SD) Number of Bouclé Profiles (dm^{-1})	
	Group I	Group II	Group I	Group II	Group I	Group II
1	0	0	*	*	*	*
2	0	4 or 4.5	*	20.98 (8.64)	*	5.53 (1.12)
3	3 or 4	6 or 6.5	23.90 (21.91)	14.13 (5.10)	4.6 (1.35)	7.2 (1.14)
4	7	8 or 8.5	12.55 (3.49)	9.86 (4.34)	6.33 (1.34)	8.26 (1.38)
5	9	9; 9.5 or 10	10.83 (2.63)	8.70 (2.57)	8.33 (1.29)	8.4 (1.35)
6	Not totally clear, but approximated to 10	Not totally clear, but approximated to 9.5	8.08 (1.93)	8.45 (1.57)	9.2 (1.52)	9 (1.31)

Figure 25 shows that the size of the profiles decreased when the rotational speed was increased. Further, it shows that the thinner, softer effect thread created larger effect profiles than the thicker, stiffer thread.

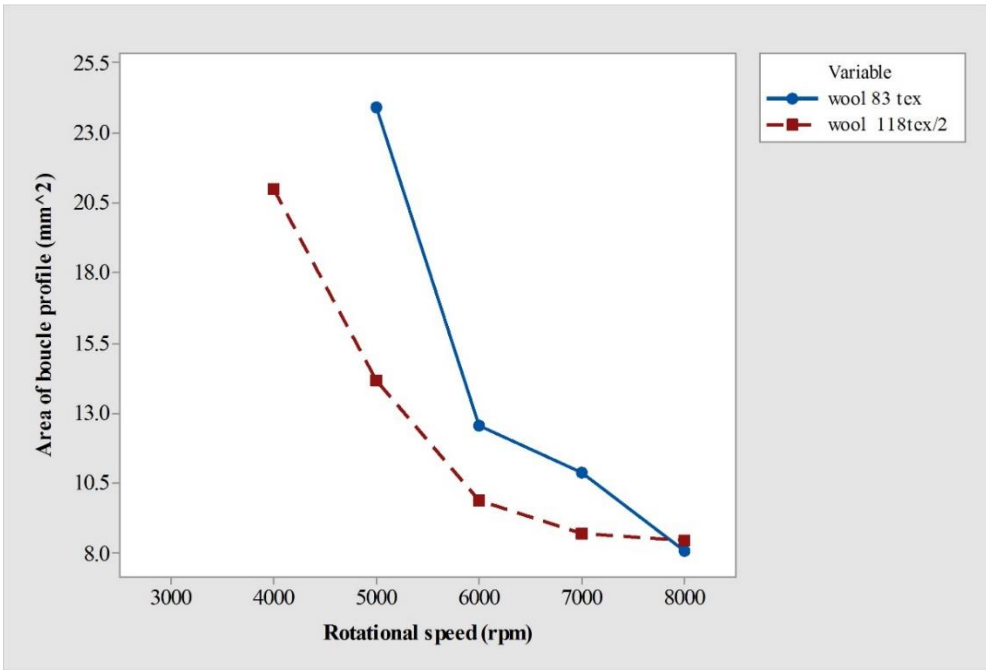


Figure 25: The Impact of Rotational Speed and Thickness of the Effect Thread on Size of Bouclé Profile

Although the data of Table 26 did not indicate any trend for the variability of the Number of Bouclé Profiles, Figure 26 shows that the variation in the Size of Bouclé Profile decreased when the rotational speed increased, i.e. when the size of the profiles decreased. Further, the variability resulting from the thick, stiff effect thread was decreasing linearly with the increase in the rotational speed. Furthermore, the variability resulting from both effect threads, the thick and the thin, were similar at the rotational speeds 6000, 7000 and 8000 pm. Therefore, it was inferred that the variation in the Size of Bouclé Profile may became related to only the machine setting rather than the thickness and type of the effect threads when the rotational speed was sufficiently high, i.e. RS=6000 rpm in this experiment.

Although the thin, soft effect thread failed to make a fancy yarn when RS=4000 rpm, the variability resulting from the thicker, stiffer effect thread was high and unacceptable. When the rotational speed became 5000 rpm, the soft effect thread resulted in high variability in the Size of Bouclé Profile, while the stiff effect thread resulted in much lower variability.

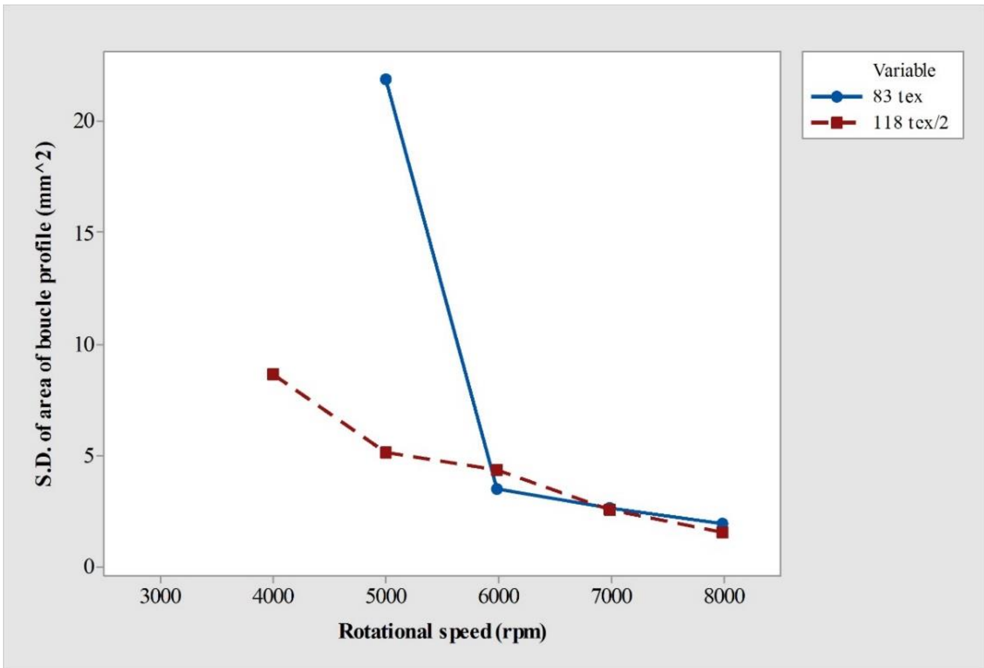


Figure 26: The Impact of Rotational Speed and Thickness of the Effect Thread on the Variation in Size of Bouclé Profile

With regard to the Number of Bouclé Profiles, it is shown in Figure 27 that the number of the profiles increased when the rotational speed was raised. Furthermore, the thicker effect thread resulted in a higher number of profiles at machine settings 2, 3 and 4, in comparison with the thinner effect thread. However, both effect threads created approximately the same number of the profiles for machine settings 5 and 6.

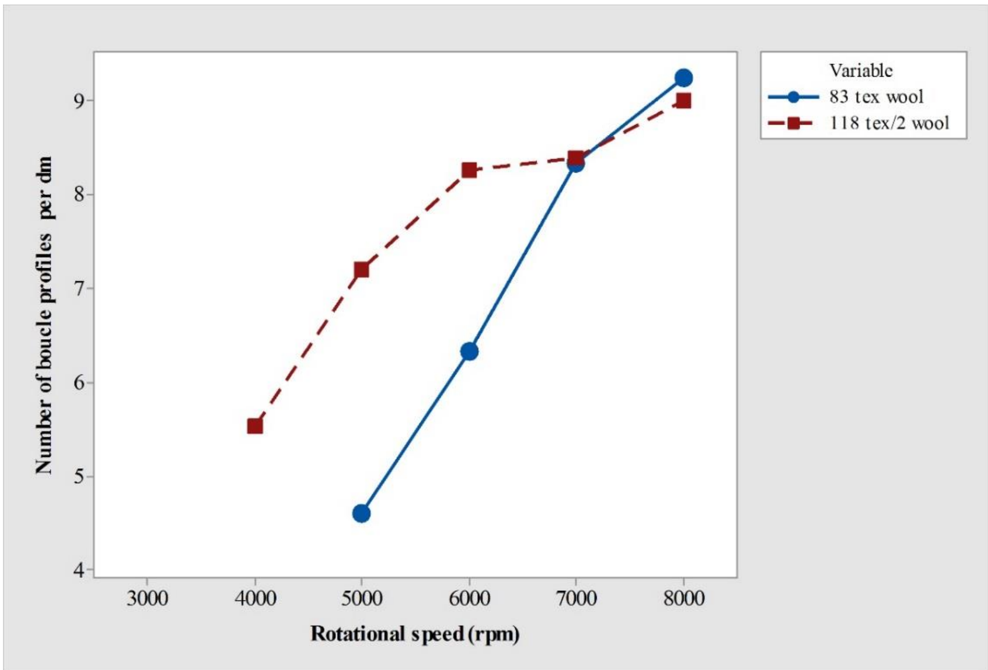


Figure 27: The Impact of Rotational Speed and Thickness of the Effect Thread on Number of Bouclé Profiles

5.6.1 Discussions

The failure of the effect thread to form helices meant the inability to make a fancy yarn. Both effect threads used in this experiment failed to form helices at the lowest level of rotational speed, i.e. 3000 rpm, used for machine setting 1. At this level of rotational speed, both effect threads flexed as extremely large arcs. Those arcs fell down according to gravity. Further, they were whirling, due to the rotational motion, but the whirling of the arcs was irregular.

Dynamically, each thread segment in the First Spinning Zone was subject to mainly the gravitational force, air drag and the centripetal force. The gravitational force normally results from the weight of the effect thread segments in the First Spinning Zone, while the rotational motion causes the centripetal force. Further, in the steady-state rotation, the centrifugal force is balanced by the centripetal force. In theory, the value of the centripetal force depends on the mass of the thread segments. Air drag is related to several factors, amongst which are condition of surface of contact between thread and air, speed of rotation of thread, and size, shape and mass of the thread segment. Except for the two low values of rotational speed, air drag was neglected at this stage of investigation for the other values of rotational speed.

The impact of the gravitational force and air drag at 3000 rpm must have been stronger than the centripetal force. Otherwise the effect threads would not have fallen down and have flexed to form large arcs. Instead, the effect threads would have formed helices. However, due to the effect of gravity, both effect threads bent downwards without making helices. Consequently, the rotational speed of 3000 rpm was not suitable to make any type of fancy yarn including bouclé yarn.

When the rotational speed became RS=4000 rpm, the thin and soft effect thread (of Group I of fancy yarns) flexed more than required and collapsed down due to gravity. Therefore, no helices and no fancy yarns resulted from it. In contrast, the thick and stiff effect thread (of Group II of fancy yarns) made a fancy yarn. This was due to its higher stiffness which prevented it from flexing down toward the ground. It is thought that the centripetal force was greater than the gravitational force. The following mathematical calculations provide the evidence to such a claim.

Consider an infinitesimally small segment *dl* of the effect thread, having a linear mass *m*. It was a simple procedure to compare its weight G (gravitational force) with the centripetal force F_c where $G = m\,dl\,g$ while $F_c = m\,dl\,r\,\omega^2$. For simplicity and since the previous two equations were similar due to the common factors *m dl*, the gravitational acceleration $g = 9.80665$ m s^{-2} was compared with the centripetal acceleration $a_c = r\,\omega^2$. Firstly the radius *r* was estimated theoretically using equation 4.42 (see Section 4.9.3) which is reproduced here as:

$$r = \frac{L_c\sqrt{\eta^2-1}}{2\pi n} \tag{5.3}$$

where L_c is the length of the core thread (or the First Spinning Zone), *n* is the number of helices formed, η is the overfeed ratio. So, for the second machine setting,

$r = \frac{40\sqrt{1.66^2-1}}{2\pi\times4}$ = 2.11 mm

The angular velocity ω (measured in radians per second) is given by the equation:

$$\omega = 2\pi\,(RS) \qquad (5.4)$$

so, the centripetal acceleration a_c = 2.11 × $(2\pi\times4000/60)^2$ =370518 mm s^{-2}. Therefore, a_c =370518 mm s^{-2} >> g=9806.65 mm s^{-2}. Consequently, the gravitational forces was neglected for its *relatively* small value for this machine setting and the machine settings 3, 4, 5 and 6 which have higher values of the rotational speed.

For all the fancy yarns, and as inferred from Figure 25 and Figure 27, the bouclé yarns made using the thinner (and softer) effect thread resulted in a lower number of larger bouclé profiles if compared with the thicker effect thread. The reason for these differences was related to the differences in number of helices in the First Spinning Zone. Such a number was always greater for the stiffer effect thread, whenever the rotational speed was lower than 7000 rpm. This level of rotational speed made the effect-thread helices touching the core thread.

Since the centripetal acceleration was much higher than that of gravity even for the low rotational speed RS=3000 rpm, the gravitational force was neglected because of its low value and effect. Consequently, the key force was the centripetal force. Since this force is related to the mass of the thread segment, the higher the mass of the thread segment the higher the centripetal force. The direction of this force is always toward the centre of rotation, that is, the axis of the helices. Therefore, this force always attempts to compress the helices to have narrower radii. Consequently, the higher this force, resulting from the greater mass of the effect thread, the narrower the radii of helices. Therefore, the heavier effect thread made narrower helices, in comparison to the lighter effect thread. Due to the equation in length of both the thick effect thread and the thin effect thread, the narrower helices, of the thick effect thread, were always associated with higher number of helices.

The critical level of the rotational speed for this experiment was approximately RS=7000 rpm. At this level, a crossover happened to the relationships for the number of bouclé profiles (Figure 27) and a crossover started to happen for the relationships given in Figure 25. The reason for the crossovers was the relatively low value of the overfeed ratio, i.e. η=166 %. This value was not sufficient to make the helices wide enough at the high levels of the rotational speed. Instead, at high rotational speed, the helices were touching the core thread, thus they were unable to become any narrower. When the effect-thread helices became touching the core thread, the thinner effect thread made helices of narrower radius, even when the number of helices was similar to that of the stiffer and thicker effect thread. Consequently, relatively smaller bouclé profiles resulted from the thinner effect thread at high rotational speeds.

It was observed that the number of helices for the thick, stiff effect thread was not stable. This variation was attributed to local variability of bending stiffness of this thread. This is because this thread was a 2-ply thread, and its cross-section was not circular; instead, it had distinctive length and width. While making the fancy yarns, the 2-ply effect thread had random changes to the spatial direction of its cross-section. When this thread bent in the direction of width of its cross-section it usually forms more helices in comparison with case when it bends in the longitudinal direction of the cross section. This is because the value of bending stiffness normally changes according to the direction of bending of beams [9], whether it is in the length or width of the cross-section. These changes are related to the differences in the value of the *Second Moment of Inertia* (I) of the cross-section [9]. Therefore, and similar to the case of beams, the value of bending stiffness of the ply effect thread is normally high when this thread bends in the direction of length of the cross-section. However, the value of bending stiffness is low when the effect thread bends in the direction of the width the same cross-section.

With regard to the variation in the Size of Bouclé Profile, there were reductions in this variation when the rotational speed was increased (Figure 26). Further, at rotational speed RS≥6000 rpm, the variability in the area of the profile was approximately similar in both groups of fancy yarn. This variation in the area of the profiles was thought to be not directly related to the rotational speed. Instead, it was related to changes made to the number of wraps. Since the number of wraps was allowed to change with the rotational speed in this experiment, high numbers of wraps corresponded to high levels of the rotational speed. Therefore, when there were more wraps, the distance between the wraps, i.e. the wrapping pitch, became shorter. So, the availability of short space may reduce the margin available for the base of bouclé profile to change width. Consequently, lower variation in area of profiles resulted.

5.6.2 Conclusions

Based on this experiment, it was concluded that:

- Thick and stiff effect threads were suitable to make multi-thread fancy yarns at low rotational speed, i.e. 3000 rpm.
- Changing the level of rotational speed affected the formation of the effect-thread helices. Further, high rotational speeds (up to 8000 rpm) led to a high number of narrow helices (up to about 10 helices) in the First Spinning Zone.
- High numbers of helices, in the First Spinning Zone, resulted in high numbers of bouclé profiles on the fancy yarn surface.
- Narrow helices of the effect thread resulted in small bouclé profiles on the fancy yarn surface.
- The thickness of the effect thread became more important than its bending stiffness in defining the structure of the resulting fancy yarn when the rotational speed was high while the number of wraps was not excessive. When the rotational speed was approximately 7000 rpm while the number of wraps was 233 wpm, and by using only one effect thread to make bouclé and fancy yarns, the thin and soft effect thread resulted in a low number of large bouclé profiles in comparison with a thick and stiff effect thread.

5.7 Testing the Input Yarns for Bending

The input threads used to make multi-thread bouclé yarns were tested for bending using the Initial Bending Frame, the Improved Bending Frame, and the Kawabata's Pure

Bending Tester KES-FB-2 while the Ring-Loop Method was used for the sake of comparison.

5.7.1 The Results of the Test Using the Initial Bending Frame

The results of testing the input threads using the Initial Bending Frame are given in Table 27. It was found that the variability of bending stiffness of the threads was high as indicated by the value of CV% was in the range 21.7 %~ 44.74 %. In practice, high variability of bending stiffness of the input threads may be reflected on the bouclé yarn structure as high variation in the size and the number of bouclé profiles.

Table 27: The Results of Measurements of Bending Stiffness of Input Threads Using the Initial Bending Frame

Sample Number	Thread Type	Colour	Resultant Linear Density tex	B: Bending Stiffness, g mm^2			Confidence Intervals, g mm^2
				Average	Standard Deviation SD	CV%	
1	Soft Acrylic	Canary, cerise	R72/2	1.199	0.361	30.098	(1.0379, 1.3594)
2	Lambswool/cotton	undyed	R120/2	4.507	1.592	35.31	(3.653, 5.362)
3	Combed cotton	Amber	R126/3	1.603	0.512	31.915	(1.320, 1.887)
4	Natural wool	Natural	R195/2	7.22	1.53	21.13	(6.379, 8.069)
5	Lambswool	Honeysuckle	R120/2	3.340	0.839	25.123	(2.848, 3.832)
6	Wool/polyamide	Aroma	R120/2	4.765	1.671	35.06	(4.016, 5.515)
7	Lambswool/viscose, 60/40	Gretna Green	R120/2	4.593	1.639	35.683	(3.738, 5.447)
8	Wool/Cotton, 50/50	Snapdragon	R163/2	8.693	3.968	45.642	(6.87, 10.52)
9	Wool/Nylon	Camel	R120/2	3.831	1.164	30.376	(3.339, 4.323)
10	Linen/Cotton	SAND	R144/2	2.697	0.823	30.50	(2.333, 3.061)
11	Lambswool 1/12s	ROSE	83	0.711	0.318	44.74	(0.5618, 0.861)
12	Pure wool, Glenshear	Fawn	R120/2	4.006	1.116	27.847	(3.499, 4.662)
13	Stiff acrylic, core thread	Beige	140	22.515	6.759	30.022	(18.60, 25.65)
14	Soft Acrylic	Canary, cerise	R72/2	1.199	0.361	30.098	(1.0379, 1.3594)
15	Cotton, (Andy's cotton)	Lt. Camel	R72/3	0.791	0.242	30.605	(0.6416, 0.9407)
16	Stiff acrylic, effect thread	Beige	140	20.630	7.031	34.08	(16.98, 24.28)
17	Soft Shetland wool	Lt. Camel	R220/2	9.392	2.737	29.144	(7.877, 10.908)
18	Lambswool/Cashmere,	Lt. Camel	R120/2	3.183	0.811	25.487	(2.720, 3.645)
19	Wool/Linen/Cotton	Purity	R180/2	9.154	2.851	31.145	(7.327, 10.981)
20	Cotton	Bleached	R295/5	15.738	4.711	29.923	
21	Cotton	Undyed	R144 /2	2.238	0.521	23.276	(1.874, 2.602)
22	Bamboo	Light green	Ne= 24s/3	1.295	0.520	40.132	(1.067, 1.522)
23	Wool (wind)	Camel	67	1.288	0.497	38.60	(1.061, 1.516)
24	Wool/angora/polyamide		67	1.676	0.376	18.91	(1.405, 2.366)
25	Wool	DK GREEN	R118/2	4.20	1.13	27.02	(3.578, 4.821)

The reasons for the variation in bending stiffness were thought to be:

1. The Initial Bending Frame itself, which could be lacking accuracy and precision;
2. The nature of the test may affect the results, especially when the length of the threads was 5 mm more than the distances between the jaws, to prevent the threads from falling down. These extra 5 mm in length was not considered when measuring the weight of specimens, nor when measuring the length of specimen.
3. The input threads were spun yarns and spun yarns are not homogeneous in the structure [11]. Spun yarns usually have several types of defect within the structure because of the raw material and the manufacturing process. In particular, neps, piecings, fly, knots, snarls, loops, crackers are example of defects, which may locally affect the bending stiffness. Further details are given in Section 2.8.4;
4. Spun threads are not homogeneous in the cross-section because of thin places, thick places and slubs which may locally affect the bending stiffness;
5. The packing density of fibres within the thread structure changes longwise as well as crosswise in the thread structure. Such changes affect both the volume density and the linear density of thread. Therefore, the distribution of mass in the threads also varies along different thread segments (i.e. longitudinal mass variation). Consequently, the weight of the thread, which affects the value of bending stiffness, is not uniformly distributed along the thread axis;
6. It was also found that some threads bent in a three-dimensional configuration. The reason for this could be the winding-in process of the threads on packages. Such a process was thought to create internal stresses within the threads. So, upon unwinding those threads off the packages, the internal stresses remained. Therefore, these internal stresses affected the threads and made them curving in a space instead of curving in a two dimension plane;
7. Most of threads used in the experimental work were two-ply threads with some others singles or three-ply threads. Therefore, the value of its bending stiffness changed according to the direction of bending, i.e. in the direction of the length or the width of its cross section, which affect the value of second moment of inertia (I) of the cross section. So, changes to this factor directly affect the bending stiffness (EI). Furthermore, when testing plied threads, the chance of getting unbalanced

plied thread structure always exists. Such a defect may shift the theoretically expected location of the point of maximum deflection of the plied thread to a different segment of the same thread along its axis. In theory, the point of maximum deflection is located at 3L/8 apart from the simple support of the thread, while the maximum deflection should be $WL^2/187\,B$ [71]; and

8. Added to all these are the error of sampling and the error of measurement which could have a profound impact on the results.

The values of bending stiffness in Table 27 did not follow normal distributions for 6 out of 24 samples. Those six samples were 3, 7, 11, 15, 16 and 18. The measurements of these samples were concentrated around the mode values. Further, high variability of the angle of maximum bending (θ) was also observed (as given in Section A-1 of Appendix A). The reasons for obtaining high variability of bending stiffness may explain the variability of angle θ.

Since the results of the Initial Bending Frame were not accurate when yarns were tested, it was decided to evaluate a more homogenous material than singles or two play yarns. Further, it was decided to compare its results against the Kawabata's Pure Bending Tester KES-2 and the Ring-Loop Method. The results of such evaluation and comparison were thought that they may give an indication about the accuracy of the Initial Bending Frame.

5.7.2 Testing the Accuracy of the Initial Bending Frame

When a rubber monofilament was tested, the results are given in details in Section A-2 of Appendix A. In summary, the results were unacceptable because the bending stiffness B= 5.603 g mm^2 and SD =2.169 g mm^2; thus, CV=38.7%. The reasons for this high CV% ratio may have been the bending frame itself and/or permanent, internal, local stresses in the rubber monofilament.

When a core-spun sewing thread having a count Ne= 2/2/3 was tested, the full results are given in Section A-3 of Appendix A. In summary, the results were also unacceptable because the bending stiffness B= 5.082 g mm^2, SD= 1.402 g mm^2; thus, CV=27.64 %. Similar to the case of the rubber monofilament, it was difficult to give a judgment about origin of this high variability, whether it is the bending frame or the thread. Additionally, the accuracy or precision of this Initial Bending Frame was still unknown.

5.7.3 Comparison between the Initial Bending Frame and the Kawabata's Pure Bending Tester KES-FB-2

It was a useful procedure to compare the results of the Initial Bending Frame (as given in Table 27) with the Kawabata's Pure Bending Tester KES-FB-2. Therefore, the input yarns were tested on the Kawabata's device. The full results are given in Section A-4 in Appendix A. The results of Kawabata were plotted against the results of the Initial Bending Frame as shown in Figure 28.

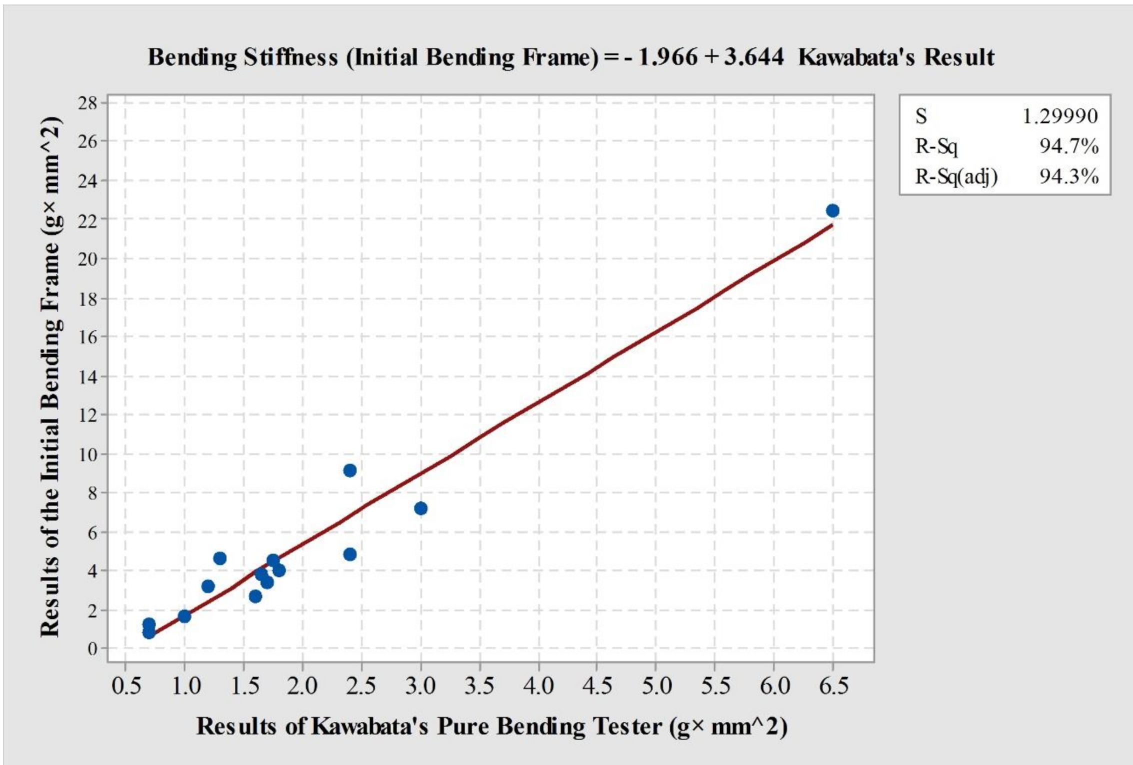


Figure 28: Comparison of the Results of Kawabata's Bending Tester and the Initial Bending Frame

Comparing both groups of results showed that the results obtained using the Initial Bending Frame were approximately three times higher than those obtained using Kawabata's device. The relationship shown in Figure 28 between those results was linear as follows:

$$\text{Results of the Initial Bending Frame} = -1.966 + 3.44 \times \text{Result of Kawabata's Device} \qquad (5.3)$$

The coefficient of correlation (r) between the two methods was high, i.e. $r = 0.9734$ and significant because the p-value was 0.000. Due to the variability of the results of the Initial Bending Frame, and the high deviation from the results of the Kawabata's device, the accuracy of the Initial Bending Frame was thought to be unacceptable. Therefore, it was decided to put the efforts towards improving the Initial Bending Frame.

5.7.4 Comparison between the Improved Bending Frame, the Kawabata's Pure Bending Tester KES-FB-2 and the Ring-Loop Method

The accuracy of the Improved Bending Frame was tested against the Kawabata' Pure Bending Tester and the Ring-Loop Method using a Ne=2/2/3 core-spun sewing thread. A summary of the results which were suitable for comparison between the three pieces of equipment is given in Table 28. The full results of the Improved Bending Frame were given in Section A-5 of Appendix A, and the full results of using the Ring-Loop Method are given in Section A-6 of Appendix A.

Table 28 shows that the Kawabata's Pure Bending Tester gave substantially smaller average values than the other methods. Further, since the results showed that the Ring-Loop Method gave higher mean values than the Beam Method, a 2-sample t-test was conducted to confirm this at a significance level $\alpha=0.90$. The results of this t-test showed that p-value=0.015. This meant that this difference between the Ring-Loop Method and Beam Method was significant. However, the variability resulting using both methods was statistically not different because the results of Levene's Test was $p=0.120$. The difference in the average value of both methods is related to the configuration of the thread while conducting the test. This is because unless the loops were perfectly circular, using equation (2.6) of the Ring-Loop Method (given in Section 2.8.1) was not exactly correct. Further, in practice, flexing the threads to make perfect, circular loops was not possible to achieve. Furthermore, it was thought that the impact of the thread faults was minimised when the threads were forced to bend as loops. In contrast, the impact of thread faults may be exaggerated when the threads were spread between the jaws of the bending frame. This relationship between the thread configuration while conducting the test and the impact of thread faults is worthy of further investigation, but is outwith the remit of this thesis. Therefore, to reduce its variability and errors, the tools used to measure the deflection distances on the Improved Bending Frame were changed from a commercial ruler to a calibrated ruler and a magnifying lens.

Table 28: Summary of the Results of Testing the Sewing Thread Using the Improved Bending Frame, the Kawabata' device and the Ring-Loop Method

Method	**Statistic**	**g mm^2**
the Kawabata's Pure Bending Tester KES-FB-2	Averages of the thread sheets	1.6, 1.6, 1.4, 1.45, and 1.35
	The grand average value	1.48
	SD of the averages	0.115
	the CV% of the sheets	7.78 %
Improved Bending Frame	Averages of the thread subgroups	2.447, 4.100, 6.031, 6.204 and 7.127
	Average of all individual measurements	5.182
	SD of the averages	1.884
	The CV of the averages	36.35 %
Ring-Loop Method	Averages of the thread subgroups	6.933, 8.824, 6.568, 6.348, and 6.153
	Average of all individual measurements	6.965
	SD of the averages	1.079
	The CV of the averages	15.49%

5.7.5 Estimating the Error of Measurements of Yarn Bending Stiffness when Using a Ruler to Measure the Distances on the Bending Frames

Generally speaking, errors may happen while preparing the sample manually or measuring the deflection y and the distance x using rulers. The commercial ruler used in Sections 5.7.1, 5.7.2, 5.7.3 and 5.7.4 had a mark each 0.5 mm. The procedure followed in the method shown in Sections 3.9, 3.9.1, 3.9.2 and 3.9.3 was to approximate the measurement of x and y into the closest mark. For example, using only the naked eye, it was possible to approximate the measurements in the x direction into the nearest 1 mm and in the y direction into the nearest 0.5 mm. However, using magnifying a lens, the accuracy improved, and it was possible to approximate the measurement in the y direction into the nearest 0.25 mm, while the approximation in the x direction remained intact. This procedure itself may generate variability. Suppose the examiner made a mistake while measuring the deflection in the y direction by 0.25 mm and in the x direction by 1 mm. The error resulting from this mistake would be estimated for the core-spun sewing thread, which had an average value of B=5.082 g mm^2, as follows:

The specimen which gave the value closest to the average was specimen 3 when L=60 mm, x=31 mm, y =1 mm, w=0.0043 g; thus, B=4.910 g mm^2 (Section A-3 in Appendix A). When errors are involved, the distance x for this specimen may have been 30, 31 or 32 mm, while the deflection y may have been 0.75, 1 or 1.25 mm. The error for all possible combinations of x and y was estimated for that particular specimen, and given in Table 29.

The estimated variability of bending stiffness when a ruler and a magnifying lens were used to measure the distances may be as high as $CV_E \approx$ 22 %. Therefore, another method of measuring the distance had to be considered, e.g. using the digital analysis of images of the threads after being bent.

Table 29: Estimation of the Errors Which may be Made by Assessor when Using the Beam Method

Combination	L (mm)	W (g)	*y* (mm)	*x* (mm)	Expected B g mm^2	Expected Error of Measurements (Expected B - 5.082) g mm^2
1	60	0.0043	0.75	30	6.450	1.368
2	60	0.0043	0.75	31	6.547	1.465
3	60	0.0043	0.75	32	6.621	1.539
4	60	0.0043	1	30	4.838	-0.244
5	60	0.0043	1	31	4.910	-0.172
6	60	0.0043	1	32	4.966	-0.116
7	60	0.0043	1.25	30	3.870	-1.212
8	60	0.0043	1.25	31	3.928	-1.154
9	60	0.0043	1.25	32	3.977	-1.105
Expected mean values					5.122	Not given
Expected SD					1.146	1.146
Expected CV%					22.37	1.146/5.082= 22.55

5.7.6 Accuracy of the Improved Bending Frame and the Digital Image Analysis

The digital image analysis technique was used, to replace the rulers and the magnifying lens for the new set of experiments, to reduce the error of measurements. The purpose of these new experiments was to estimate the accuracy of the Improved Bending Frame. The objective was to test materials, which were expected to have low variability, in order to obtain an idea about the variability which may result from the Improved Bending Frame itself. Therefore, paper and plastic strips were tested as described in Section 3.9.5. Firstly, the paper strips were tested without considering a correction factor ε, which was also defined in Section 3.9.4. The results of this test are given in Table 30.

Table 30: The Results of Testing Strips of Paper on the Improved Bending Frame Using Digital Image Analysis

Specimen	*L* (mm)	*x* (mm) Uncorrected	*y* (mm) Uncorrected	w (g)	B: Bending Stiffness (g mm^2)	Linear Density (tex)	$B_i - B_{average}$ (g mm^2)
1	110	64.20	1.05	0.0603	413.92	548.18	5.44
2	110	64.68	1.10	0.0608	398.22	552.73	-10.26
3	110	59.53	1.04	0.0597	410.18	542.73	1.70
4	110	65.03	0.88	0.059	482.82	536.36	74.34
5	110	67.32	1.04	0.0582	400.50	529.09	-7.98
6	110	64.07	1.04	0.0587	406.84	533.64	-1.63
7	110	60.96	0.93	0.0598	461.80	543.64	53.32
8	110	62.63	0.99	0.0606	441.04	550.91	32.56
9	110	60.66	1.21	0.06	355.81	545.45	-52.67
10	110	51.71	0.99	0.0563	380.37	511.82	-28.11
11	110	62.18	1.13	0.0605	385.53	550.00	-22.95
12	110	59.42	1.10	0.0594	385.67	540.00	-22.81
13	110	59.14	1.00	0.0565	403.01	513.64	-5.47
14	110	58.37	1.07	0.0578	383.80	525.45	-24.68
15	110	58.57	1.21	0.0606	356.22	550.91	-52.26
16	110	64.43	0.98	0.0597	439.00	542.73	30.53
17	110	59.18	1.18	0.0595	359.74	540.91	-48.74
18	110	55.23	1.21	0.0642	368.57	583.64	-39.91
19	110	60.96	1.21	0.0595	353.16	540.91	-55.32
20	110	54.39	0.69	0.0584	583.37	530.91	174.89
Average					408.48	540.682	
SD					54.37	15.351	
CV%					13.31	2.84	

It was found that the average value of bending stiffness of the paper strips was 408.48 g mm^2, and the standard deviation was 54.37 g mm^2. This made the CV= 13.31 %. This level of variation was the lowest level possible to obtain so far on the bending frame. Since a laser cutter was used to prepare specimens from paper, it was not expected to have variation in dimensions between the specimens. Moreover, the variability associated with the linear density of these specimens was low, i.e. CV= 2.84 %. Therefore, it was not possible to tell whether the variation in bending stiffness has resulted from the Improved Besting Frame or the paper strips.

The plastic strips were tested twice. Firstly, at a fixed length of 110 mm. Secondly, by varying the testing length because the length of effect thread and the overfeed ratio varied from one experiment to another. All measurements obtained were corrected using the correction factor ε.

When the fixed length test was conducted, Table 31 shows that the average value of bending stiffness was 225.97 g mm^2 and the standard deviation was 12.66 g mm^2; thus, the CV=5.6%. Therefore, the variation for the bending stiffness was relatively low, and the variation associated with the linear density was also low. Further, since the widths of the specimens were set manually, the variation of bending stiffness was related to variation in the dimensions instead of the linear density. Consequently, the low variation in the results of this particular experiment gave evidence about the accuracy of the Improved Bending Frame and the digital image analysis. Therefore, testing an isotropic, uniform material on this the Improved Bending Frame may give an acceptably low value of variability. Further, the variability which resulted when testing the paper strips may have been related to the material instead of the bending frame.

Table 31: The Results of Testing the First Group of Plastic Strips at a Constant Specimen Length

Specimen	*L* (mm)	*x* (mm) Corrected	*y* (mm) Corrected	w (g)	B: Bending Stiffness (g mm^2)	Linear Density (tex)	$B_i - B_{average}$ (g mm^2)
1	110	63.28	2.31	0.0719	224.37	653.64	-1.608
2	110	61.38	2.29	0.0728	228.56	661.82	2.589
3	110	60.74	2.30	0.07	218.44	636.36	-7.535
4	110	58.07	2.27	0.0704	219.97	640.00	-6.003
5	110	62.86	2.40	0.0712	213.80	647.27	-12.177
6	110	63.16	2.33	0.0705	218.10	640.91	-7.877
7	110	57.84	2.33	0.0694	210.97	630.91	-15
8	110	64.55	2.34	0.0696	214.32	632.73	-11.652
9	110	61.16	2.34	0.0746	229.08	678.18	3.111
10	110	61.38	2.37	0.0716	217.21	650.91	-8.767
11	110	60.63	2.17	0.0723	239.05	657.27	13.077
12	110	65.30	2.29	0.0721	226.63	655.45	0.661
13	110	63.36	2.33	0.0731	226.16	664.55	0.184
14	110	61.95	2.18	0.0714	235.76	649.09	9.782
15	110	63.34	2.35	0.0714	219.02	649.09	-6.956
16	110	65.15	2.33	0.0701	216.62	637.27	-9.354
17	110	59.63	2.12	0.0711	239.74	646.36	13.771
18	110	58.97	2.16	0.0708	233.61	643.64	7.641
19	110	56.70	2.17	0.0685	221.90	622.73	-4.078
20	110	64.26	2.02	0.0746	266.17	678.18	40.199
Average					225.97	648.82	
SD					12.66	14.52	
CV%					5.60	2.24	

When a varying length of specimen was used, Table 32 shows that the average value of bending stiffness was 186.25 g mm^2 and the standard deviation was 24.41 g mm^2; thus, the CV=13.10%. The variation of bending stiffness was higher than that obtained in the previous test. Initially, it was thought that this variation resulted because of the variation in the dimensions of the specimens instead of the material or the method itself. However, comparing the mean values of bending stiffness shown in Table 31 and Table 32 shows a considerable difference between them. Additionally, further examination to the individual values of bending stiffness in Table 32 shows that shorter lengths of the specimens yielded lower values of stiffness, while increasing those lengths increased the calculated value of bending stiffness. The reason for this variability in the results was thought to be related to differences in pressure on the fixed ends of specimens, which was initially maintained using adhesive tape. This problem required a solution, so a pressure peg was used to give stable pressure on the fixed end of specimens for the new tests.

Table 32: The Results of Testing the Second Group of Plastic Strips at Variable Specimen Lengths

Specimen	*L* (mm)	*x* (mm) Corrected	*y* (mm) Corrected	w (g)	B: Bending Stiffness (g mm^2)	Linear Density (tex)	$B_i - B_{average}$ (g mm^2)
1	90	51.01	1.25	0.0586	184.94	651.11	-1.31
2	90	40.74	1.17	0.0579	176.56	643.33	-9.69
3	90	54.44	1.50	0.0577	151.20	641.11	-35.05
4	90	50.58	1.25	0.0606	191.09	673.33	4.84
5	90	44.94	1.41	0.0579	155.81	643.33	-30.44
6	95	53.44	1.75	0.0594	157.36	625.26	-28.89
7	95	50.54	1.83	0.0654	163.69	688.42	-22.56
8	95	53.06	1.47	0.0633	199.46	666.32	13.21
9	95	53.53	1.78	0.0627	163.34	660.00	-22.91
10	95	53.21	1.53	0.0651	197.16	685.26	10.91
11	100	62.60	1.64	0.0643	209.26	643.00	23.01
12	100	58.65	1.69	0.0638	204.38	638.00	18.13
13	100	55.38	1.93	0.0691	193.17	691.00	6.91
14	100	57.20	1.71	0.0658	208.35	658.00	22.10
15	100	56.20	1.93	0.0512	143.43	512.00	-42.82
16	105	60.10	2.09	0.0677	203.05	644.76	16.80
17	105	63.16	2.17	0.0663	190.91	631.43	4.66
18	105	59.36	1.81	0.0681	235.64	648.57	49.39
19	105	56.83	2.25	0.0653	180.37	621.90	-5.88
20	105	59.49	1.86	0.0641	215.88	610.48	29.63
Average					186.25	643.83	
SD					24.41	37.95	
CV%					13.10	5.89	

5.7.7 Reliability of the Improved Bending Frame and Digital Image Analysis at a Constant Specimen Length

Testing the reproducibility of the Improved Bending Frame, when used in conjunction with the digital image processing, was conducted using the $\overline{x}$-SD Control Chart. Plastic strips (called the First Group of plastic strips) were tested, and the Correction Factor ε was used to correct the measured values of distance. The specific bending stiffness (measured in g mm^2 tex^{-2}) was used to plot the control chart of Figure 29 while the full results are given in Section A-7 of Appendix A. Figure 29 shows that the average and standard deviation of the subgroups, from 1 to 14, did not exceed the Upper Control Limit (UCL) or the Lower Control Limit (LCL). The total average value was 0.412284 g mm^2 tex^{-2} while the SD was 0.031074 g mm^2 tex^{-2}. This made the CV=7.54 %. Since this variation was low, even over a week of conducting the test, the Improved Bending Frame may be reliable to test threads.

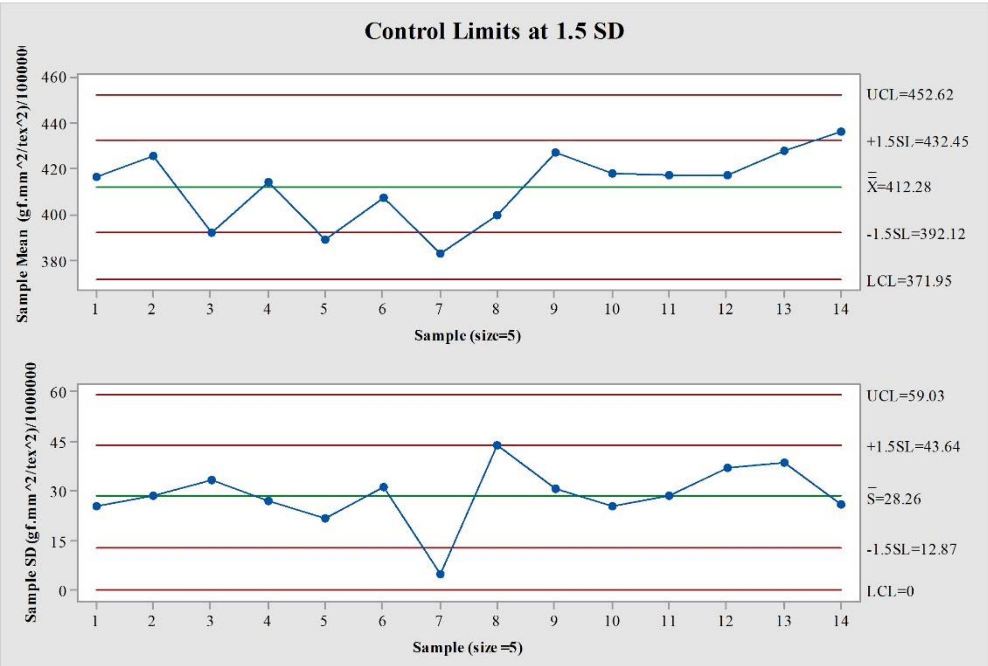


Figure 29: $\overline{X}$-SD Control Chart for the Testing Process Using the Improved Bending Frame

It is worth noting that although it was not possible to account for the variation in dimensions of the specimens, the variation for the linear density was available. The average value was 640.94 tex, SD= 20.51 tex, and the CV=3.20 %. The values for the bending stiffness of the samples were: the average B=169.20 g mm^2, SD=12.69 g mm^2 and the CV=7.50 %.

5.7.8 Reliability of the Improved Bending Frame and the Digital Image Analysis at a Variable Specimen Length

The test of reliability of the Improved Bending Frame was conducted using the Second Group of plastic strips. It was found that the average value of bending stiffness was 182.47 g mm^2 and the standard deviation was 23.7 g mm^2; thus, the CV=12.99%. The full measurements and results are given in Section A-8 of Appendix A. Comparing those results with the results in Section A-7 of Appendix A indicates that the variability of the measurement increased when the length of the sample was changed.

5.7.9 Conclusions for Testing the Input Yarns for Bending

- Relatively low variability of bending stiffness resulted when testing uniform material specimens at constant length, while variable lengths of the specimens resulted in higher variability.
- The variability resulting from the Improved Bending Frame using the digital image analysis was low, thus acceptable.

5.7.10 Recommendations to Test the Input Yarns for Bending

- Using the Improved Bending Frame and the digital image analysis is sufficiently accurate to test the input yarns for bending at a constant test length.
- To make the test comparable with the Kawabata's Pure Bending Tester KES FB-2, a sample size of 20 specimens should be chosen to measure the bending stiffness of the input yarns.

5.7.11 Testing the Input Yarns for Bending on the Improved Bending Frame Using the Digital Image Analysis

Based on the aforementioned recommendations, the input yarns were tested again on the Improved Bending Frame using the digital image analysis; the results are given in Table 33 below. By comparing the new results and the older results, it is shown that, except yarn 7 and yarn 15, the new values of bending stiffness were significantly lower than the older values. However, except yarn 3 and yarn 15, the variation of the new results and the older results were not significantly different. Therefore, due to significantly lower new mean values, the new CV values were significantly higher than the older CV values. The exceptions to this were the cases of yarns 3, 12 and 23. The increase in the sensitivity of the Beam Method via using the Improved Bending Frame and the digital image analysis was the reason for such differences in the measurements. This is because it helped minimising the error of estimation of bending stiffness. Such an error was estimated in Section 5.7.5 and its CV_E% was as high as 22 % for only one specimen. Since the difference in the CV values between the new measurements and the older measurements was less than CV_E, it is concluded that the new measurements were accurate although they possessed higher variability. Further investigations to the origin of this variability may be related to the variability in the structure of the input threads, i.e. spun yarns. So, the variation in the bending stiffness may be used as a measure to the uniformity and evenness of the structure of spun yarns, whether they are singles, 2-ply or 3-ply. However, such a study is beyond the scope of this research which is related to the fancy yarn structure instead of the uniformity of the structure of ordinary spun yarns.

Table 33: Results of Testing the Input Yarns on the Improved Bending Frame and Using the Digital Image Analysis

Sample Number	Thread Type	Colour	Resultant Linear Density tex	B: Bending Stiffness, Older Results				B: Bending Stiffness, New Results			t-test	Leven's Test
				Average g mm^2	Standard Deviation, g mm^2	CV%	Confidence Intervals of the Average, g mm^2	Average g mm^2	Standard Deviation, g mm^2	CV%	p-value	p-value
1	Soft Acrylic	Canary, cerise	R72/2	1.234	0.361	30.098	(1.0379, 1.3594)	0.650	0.154	23.76	0.000	0.034
2	Lambswool/cotton	undyed	R120/2	4.507	1.592	35.31	(3.653, 5.362)	3.662	1.774	48.46	0.077	0.945
3	Combed cotton	Amber	R126/3	1.603	0.512	31.915	(1.320, 1.887)	1.579	0.774	48.99	0.458	0.533
4	Natural wool	Natural	R195/2	7.22	1.53	21.13	(6.379, 8.069)	5.249	1.601	30.49	0.000	0.905
5	Lambswool	Honeysuckle	R120/2	3.340	0.839	25.123	(2.848, 3.832)	2.518	0.966	38.34	0.000	0.533
6	Wool/polyamide	Aroma	R120/2	4.765	1.671	35.06	(4.016, 5.515)	3.183	1.671	52.51	0.005	0.413
7	Lambswool/viscose, 60/40	Gretna Green	R120/2	4.593	1.639	35.683	(3.738, 5.447)	3.835	1.033	26.93	0.001	0.001
8	Wool/Cotton, 50/50	Snapdragon	R 163/2	8.693	3.968	45.642	(6.87, 10.52)	8.636	4.324	50.07	0.484	0.862
9	Wool/Nylon	Camel	R 120/2	3.831	1.164	30.376	(3.339, 4.323)	2.963	1.212	40.90	0.020	0.477
10	Linen/Cotton	SAND	R 144/2	2.697	0.823	30.50	(2.333, 3.061)	2.029	0.872	42.97	0.014	0.802
11	Lambswool 1/12s	ROSE	83	0.711	0.318	44.74	(0.5618, 0.861)	0.549	0.229	41.24	0.043	0.952

5.8 The Influence of Bending Stiffness of the Effect Threads on the Structure and Quality of Bouclé Yarns

Table 34 highlights the quality parameters of bouclé yarn in terms of the values of the average and the standard deviation.

Table 34: Results of Testing the Impact of Stiffness of the Effect Threads on the Quality Parameters of Bouclé Yarn

Boucle Yarns	Size of Bouclé Profile mm^2	SD of Size of Bouclé Profile mm^2	Number of Bouclé Profiles dm^{-1}	SD of Number dm^{-1}	ShF of Bouclé Yarn $mm^2\ dm^{-1}$
Yarn 1	14.74	4.37	14.27	2.98	210
Yarn 2	15.06	4.2	12.4	3.13	186
Yarn 3	16.64	2.86	10	1.76	166
Yarn 4	18.88	5	6.46	1.92	122
Confirmation Yarn 1	13.85	4.79	11.79	2.404	163
Confirmation Yarn 2	14.79	4.39	10.33	2.257	153

In terms of the Size of Bouclé Profile, when the bending stiffness was increased, the average value of Size of Bouclé Profile also increased. Raising the stiffness of the effect threads from 1.579 to 18.3 g mm^2 led to an increase in the Area of Bouclé Profile from 14.74 to 18.88 mm^2. However, Table 34 shows that the number of bouclé profiles approximately halved from 14 to 6 profiles per decimetre. The total impact of these changes was approximately an 88 $mm^2\ dm^{-1}$ (i.e. 41 %) reduction in the Shape Factor of Bouclé Yarn. These changes in the Shape Factor of Bouclé Yarn were attributed to reduction in the Number of Bouclé Profiles. This is because the gain in the area of bouclé projection (which is a positive contribution to the structure) had a weaker impact than the loss in the number of the profiles (which is a negative contribution). Therefore, the value of the Shape Factor of Bouclé Yarn decreased when using stiffer effect threads. In practice, this meant that stiffer effect threads reduced the Absolute Fancy Bulkiness of Bouclé Profiles.

5.8.1 Regression Analysis

The numerical data of Table 34 were used to draw the plots of Figure 30, Figure 31 and Figure 32.

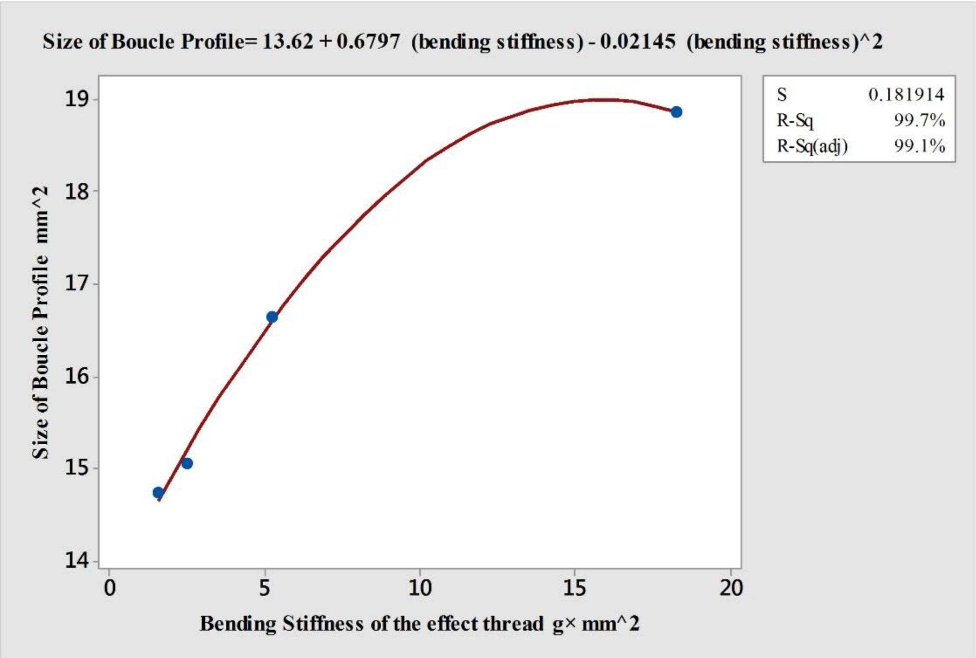


Figure 30: Relationship between the Size of Bouclé Profile and Bending Stiffness of Effect Threads

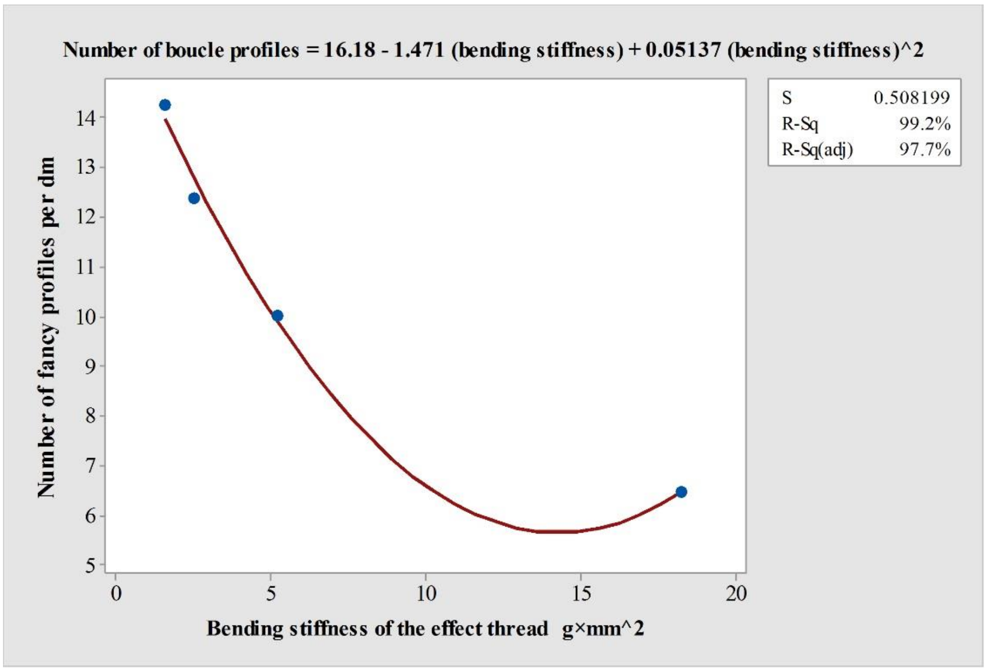


Figure 31: Relationship between the Number of Bouclé Profiles and Bending Stiffness of Effect Threads

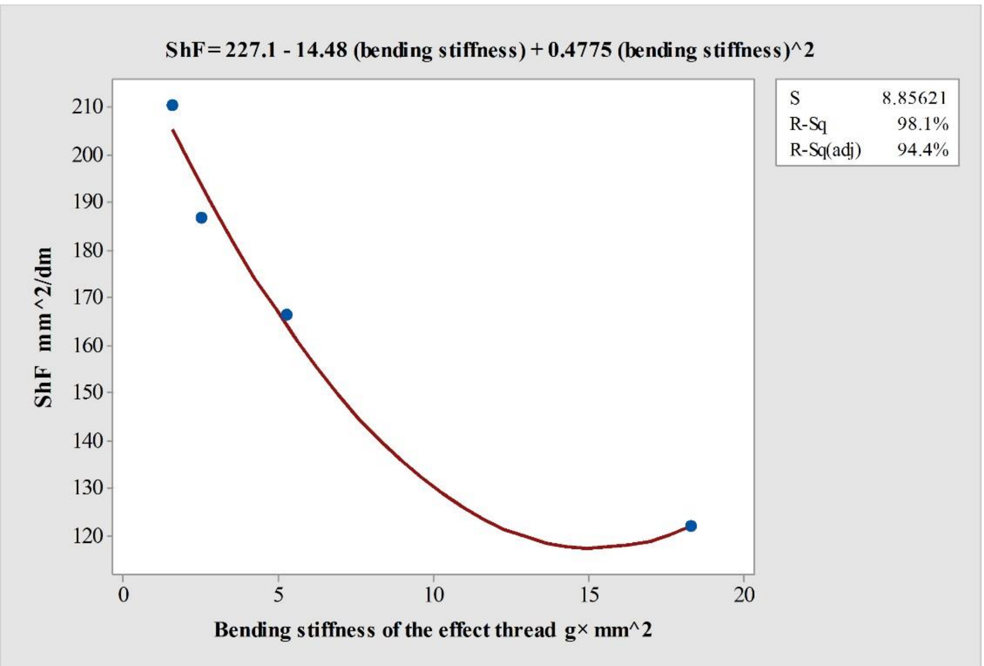


Figure 32: Relationship between the Shape Factor of Bouclé Yarn and Bending Stiffness of Effect Threads

Figure 30, Figure 31 and Figure 32 show the relationships between the quality parameters of bouclé yarn and the bending stiffness of the effect threads. Those relationships were represented by quadratic regression models as follows:

$$A = 13.62 + 0.6797\,(B_e) - 0.02145\,(B_e)^2 \qquad (5.6)$$

$$\delta = 16.18 - 1.471\,(B_e) + 0.05127\,(B_e)^2 \qquad (5.7)$$

$$ShF = 227.1 - 14.48\,(B_e) + 0.4775\,(B_e)^2 \qquad (5.8)$$

Where: A is the Size of Bouclé Profile, measured in mm^2; δ is the Number of bouclé Profiles, measured in dm; ShF is the Shape Factor of Fancy (Bouclé) Yarn, measured in $mm^2\ dm^{-1}$; and B_e is the bending stiffness of the effect thread.

The statistical study of those regression models is given in Table 35.

Table 35: The Statistical Study of the Three Regression Models of the Quality Parameters

Regression Model	Predictor Term (B_e)	P-value of Sequential ANOVA Testing	Accuracy of the Regression Line	P-value of Simple ANOVA Testing
Size of Bouclé Profile	**Linear**	0.032	SE= 0.18 mm^2 R^2 = 99.7% R^2 (adj)= 99.1%	0.056
	quadratic	0.141		
Number of Bouclé Profiles	**Linear**	0.060	SE=0.5 dm^{-1} R^2 =99.2% R^2 (adj)=97.7%	0.087
	quadratic	0.164		
ShF of Bouclé Yarn	**Linear**	0.049	SE= 8.8 $mm^2\ dm^{-1}$ R^2 = 98.1% R^2 (adj)= 94.4%	0.136
	quadratic	0.292		

This table shows that the linear terms, of relationships 5.7, 5.8 and 5.8, were all significant because the corresponding p-values were all smaller than α=0.10. Further, those regression models had high theoretical accuracy due to the high values of R^2 and adjusted R^2 which indicated strong relationships between the responses' values and the terms included in the regression models. Due to the quadratic terms, the regression lines were approximately fitting to the actual data and the regression models had low levels of variability of measurements around the regression lines. However, the quadratic terms were all not significant, so the previous three relationships shown in Figure 30, Figure 31 and Figure 32 can be represented by linear regression models. Furthermore, the overall significance of relationships 5.6 and 5.7 were secured because the resulting p-values of the simple One-way ANOVA testing were smaller than α=0.10. However, the relationship between the Shape Factor of Fancy (Bouclé) Yarn and the bending stiffness of the effect threads can be significant only by using a linear analysis approach. By doing so, relationship 5.8 became:

$$ShF = 203.1 - 4.606\ (B_e) \tag{5.9}$$

However, the accuracy of the prediction was reduced because SE= 14.15 $mm^2\ dm^{-1}$, R^2 = 90.5% and R^2 (adj)= 85.8%.

5.8.2 Discussion and Physical Explanation

The results of this experiment may be explained by relying on the results of observing of the First Spinning Zone as detailed in Sections 4.9, 5.6 and all subsections related to them. So, the results related to the Size of Bouclé Profile were explained by considering the nature of bending. The effect thread(s) usually bends in the First Spinning Zone to form helices around the core thread. When the effect thread(s) was relatively stiff, the thread(s) did not bend easily in order to make the helices. Instead, it bent in a relatively large arc, so wide helices have resulted. Therefore, the resulting bouclé profiles were relatively large in size. Furthermore, this bending behaviour of the effect thread(s) was also restricted by the length of the effect thread(s) in the First Spinning Zone. Due to the constant overfeed ratio, a relatively stiff effect(s) thread may have bent in only a few places along its axis. Consequently, a low number of helices may have resulted, so large fancy profiles were made on the ultimate bouclé yarn. In contrast, a softer effect thread(s) may have bent in several places along its axis to form more helices. Since the overfeed ratio was constant, a softer effect thread(s) made a higher number of narrower helices than a stiffer effect thread(s). Consequently, more smaller bouclé profiles were made on the ultimate fancy yarn. Moreover, the mechanism of making the bouclé profiles from the effect-thread helices in the Second Spinning Zone were as follows:

The binder pressed the effect thread(s) to the core thread in the Second Spinning Zone in order to combine them all together. However, because of the helical configuration of the effect thread(s), the binder imposed pressure on the effect thread(s) only at their points of contact to force them to bend again. Subsequently, remaining sections of the effect-thread helices were free of pressure, and therefore, they formed the fancy profiles.

When the effect thread(s) was soft, it may have had several potential points for bending. Therefore, due to the binder pressure in the Second Spinning Zone, the helices of the soft effect thread(s) bent and deformed in more than one place simultaneously (Figure 33 (a). Consequently, they formed relatively small bouclé profiles in those sections. However, the stiff effect thread(s) was more resistant to the pressure of the binder and to bending. Therefore, it only bent properly at the points that had locally low value of bending stiffness. Those points were sufficiently less resistant to bending than the remaining segments of the stiff effect thread(s) (Figure 33 (b)). Those weak points existed because of the variability of bending stiffness.

The bouclé yarn that was made using the relatively stiff effect threads had large bouclé profiles in a few segments of the yarn while the other segments were compact (Figure 33 (b)). This is because the lengths of effect thread in the compact segments were sufficiently stiff to resist the pressure of the binder; thus, when it bent, it made shallow arcs with high values of curvature. The resulting fancy profiles in the compact segments were waves, arcs, corrugations, and spirals. The extra lengths of the effect threads needed to form larger fancy profiles, in the sections free of the binder pressure, migrated from the neighbouring compact sections on the fancy yarn. The spiralling configuration of the binder within the hollow spindle and the forward movement of the intermediate product of fancy yarn within the hollow spindle helped forming the migration phenomenon.

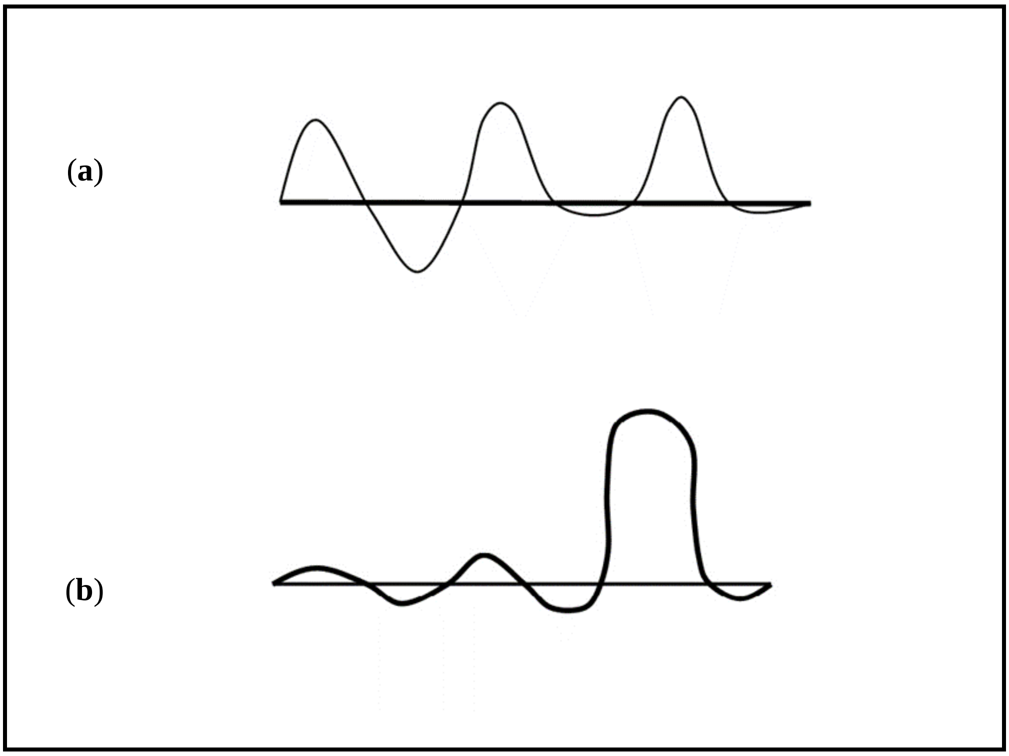


Figure 33: Deformation of the Effect-thread Helices due to Pressure of the Binder; (a) Soft Effect Thread; (b) Stiff Effect Thread

5.8.3 Model Testing and Confirmations of the Results

To test the accuracy of the regression models 5.6, 5.7 and 5.8 practically, two extra bouclé yarns were made and tested. A comparison between theoretical values and the actual values is given in Table 36. The deviations in the value of ShF were calculated and were -9.79 % and -14.39 % for the first and the second confirmation yarn, respectively.

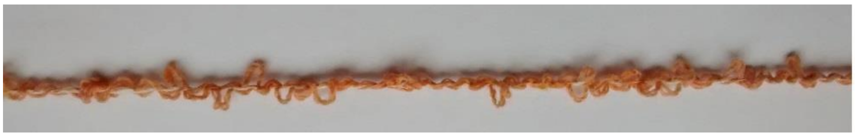
Table 36: Results of Testing the Models of Importance of Bending Stiffness of the Effect Thread to the Bouclé Yarn Structure

Bouclé Yarn Property	Confirmation Yarn 1 B_e= 3.183 g mm^2			Confirmation Yarn 2 B_e= 3.835 g mm^2		
	Predicted Value	Actual Value	Deviation from the Predicted Value %	Predicted Value	Actual Value	Deviation from the Predicted Value %
Size of bouclé profile, mm^2	15.56	13.8	-11.3	15.91	14.8	-6.97
Number of bouclé profiles, dm^{-1}	12.02	12.27	2.07	11.29	10.33	-8.5
ShF, mm^2 dm^{-1}	181.01	163.292	-9.79	178.59	152.88	-14.39

The deviation for those two confirmation bouclé yarns was acceptable, even though it was relatively high for the second yarn. This is because the fancy yarn structure is already based on deliberate variation. Additionally, the variation in bending stiffness of the effect threads used to make the confirmation cones was high, i.e. the CV was 32.97 % and 35.7 % for the effect threads of the first and second confirmation yarn, respectively. Further, there is the impact of variability of the machine. Therefore, deviation up to 15% from the predicted values was also accepted.

5.8.4 Subjective and Morphological Study of the Bouclé Yarns

Figure 34 shows images of the bouclé yarns made for this experiment, including the two confirmation yarns. Although this figure shows 2D images of 3D structures, and only over short lengths of the bouclé yarns, due to the capability of the microscope used, it is inferred from this figure that:



Yarn 1

Yarn 2

Yarn 3

Yarn 4

Confirmation Yarn 1

Confirmation Yarn 2

Figure 34: Images of Bouclé Yarns Made to Show the Importance of Bending Stiffness of the Effect Thread to the Bouclé Yarn Structure

- All bouclé yarns shown appear to have bouclé profiles, waves and sigmoidal sections. Those bouclé yarns did not have loops or snarls or knots.
- The bouclé yarns were different in their morphology and appearance.
- Yarns 1 and 2 had less compact structure than yarns 3 and 4.
- Yarn 1 had larger and more clusters of bouclé profiles that all other bouclé yarns.
- The distribution of the bouclé profiles over the yarn structure was better for yarn 2 than for yarns 1, 3 and 4.
- Yarn 3 had more wavy sections than all other bouclé yarns including the two confirmation yarns. Further, leaving the bouclé profiles aside, those wavy sections of yarn 3 may make the structure similar to the structure of gimp yarns. This property of yarn 3 not seen in yarn 4 and may have resulted due to the use of thicker effect threads to make yarn 3.
- Yarn 4 had also more sigmoidal sections than all other bouclé yarns including the two confirmation yarns.
- The bouclé profiles were better shaped for yarns 1 and 2 than that for all other yarns, while tilted or unbalanced bouclé profiles dominated over the two confirmation yarns. The reason for such unbalanced configuration of the bouclé profiles may be related to the input threads which were two-ply mixed yarn each.
- The number of bouclé profiles was high for bouclé yarns 1, 2 and the two confirmation yarns which all had bending stiffness lower than 4 g mm^2 for the effect components.

In summary, given the settings of the machine and the type of materials used, as the bending stiffness of the effect threads increases, the bouclé structure changed its morphology from having high number of bouclé profiles to low number of bouclé profiles. Further, the number of wavy or sigmoidal sections increases by increasing the stiffness of the input threads. Furthermore, clustered bouclé profiles appeared when using the softest (for yarn 1) and the stiffest (for yarn 4) effect threads.

5.8.5 Contribution of the Linear Density of the Input Threads to the Results

Ideally, the input effect threads for this experiment should all have the same thickness or linear density, but different bending stiffness. However, it was difficult to obtain threads with tailored values of thickness and bending stiffness. Further, it was not possible to find threads which had incremental increases in the value of bending stiffness or linear density. So, the property of interest of the input effect threads when analysing the results were their value of bending stiffness regardless of their thickness. However, when using the effect thread thickness to analysis the results, Figure 35 and Figure 36 show that the linear density of the effect threads did not have any clear mathematical relationship with the area or the number of bouclé profiles. Therefore, the results were only related to the bending stiffness of the effect threads. So, the bending stiffness of the effect threads was the main influential factor.

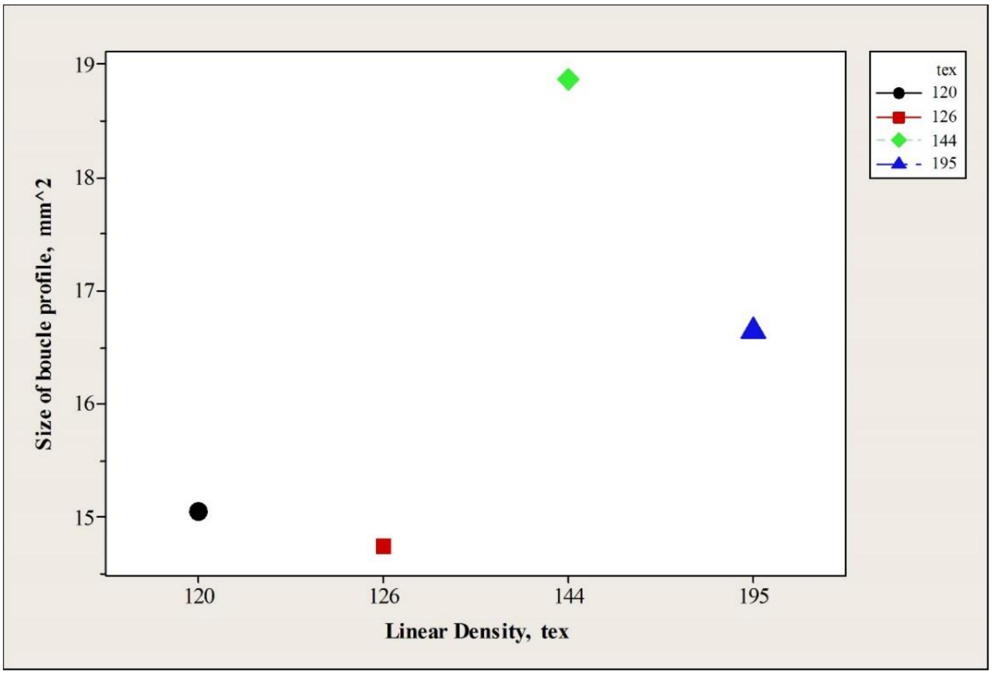


Figure 35: Plot of Linear Density of Effect Threads and the Size of Bouclé Profile

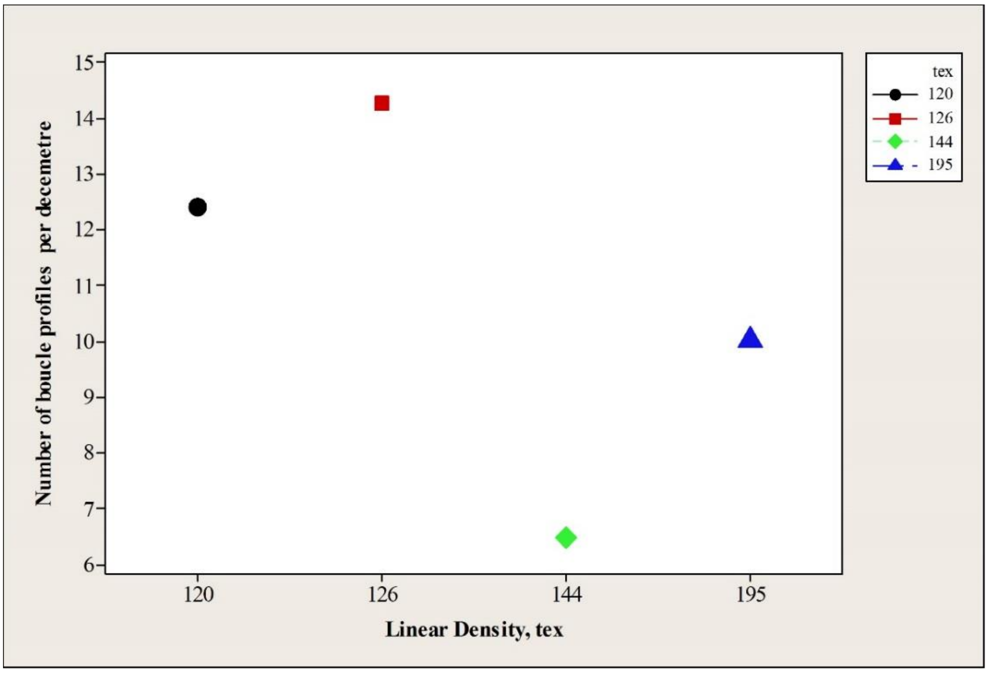


Figure 36: Plot of Linear Density of Effect Threads and the Number of Bouclé Profiles

5.8.6 Conclusions

- Eleven times increase in the value of bending stiffness of the effect threads (from 1.579 to 18.3 g mm^2), increased the average Size of Bouclé Profile significantly by approximately 4 mm^2. However, it reduced the average Number of Bouclé Profiles significantly by half.
- Those changes in the area and number of bouclé profiles were reflected as a reduction to the Absolute Fancy Bulkiness of Bouclé Profiles by 85 mm^2 dm^{-1} as measured by the Shape Factor of Bouclé Yarn.
- Therefore, the stiffer the effect threads, the lower the Number of Bouclé Profiles (and semi-bouclé profiles), the greater the Size of Bouclé Profile, and the lower the value of the Shape Factor of Fancy (Bouclé) Yarn.

5.9 The Influence of the Bending Stiffness of the Core thread on the Structure and Quality of Bouclé Yarn

Table 37 gives the results of this experiment, which did not show any clear difference between the fancy yarns. Therefore, the differences between the bouclé yarns were assessed using the One-Way ANOVA testing.

Table 37: The Results of Testing the Influence of the Bending Stiffness of the Core thread on the Structure of Bouclé Yarn

Bouclé Yarn	Size of Bouclé Profile (mm^2)	SD of the Size (mm^2)	Circularity Ratio of Bouclé Profile (%)	SD of the CR (%)	Number of Bouclé Profiles (dm^{-1})	SD of the Number (dm^{-1})
yarn 1	9.68	3.54	52.17	20.34	8.9	1.2
yarn 2	11.21	4.28	58.51	19.32	7.9	1.2
yarn 3	13.88	5.49	53.71	20.95	8	1.4
yarn 4	11.98	3.17	53.71	20.10	8.2	1.6
yarn 5	11.9	4.91	50.91	15.38	8.6	1.4
yarn 6	10.89	3.64	55.60	13.89	8.4	1.4

Figure 37 shows the 95% confidence intervals for the Size of Bouclé Profile. The p-value of the ANOVA test was 0.221. Therefore, these differences were statistically not significant.

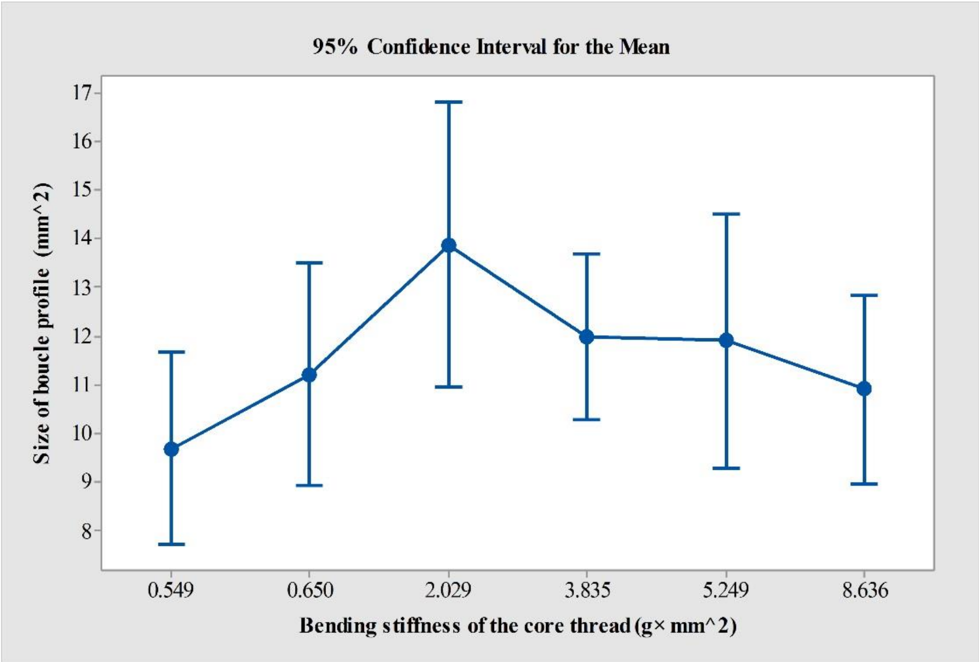


Figure 37: Interval Plot for the Influence of the Bending Stiffness of the Core Thread on the Size of Bouclé Profile

Figure 38 shows the 95% confidence intervals for the Number of Bouclé Profiles. The p-value of the ANOVA testing was 0.289. Therefore, the bouclé yarns appeared to have statistically similar numbers of bouclé and semi-bouclé profiles per decimetre.

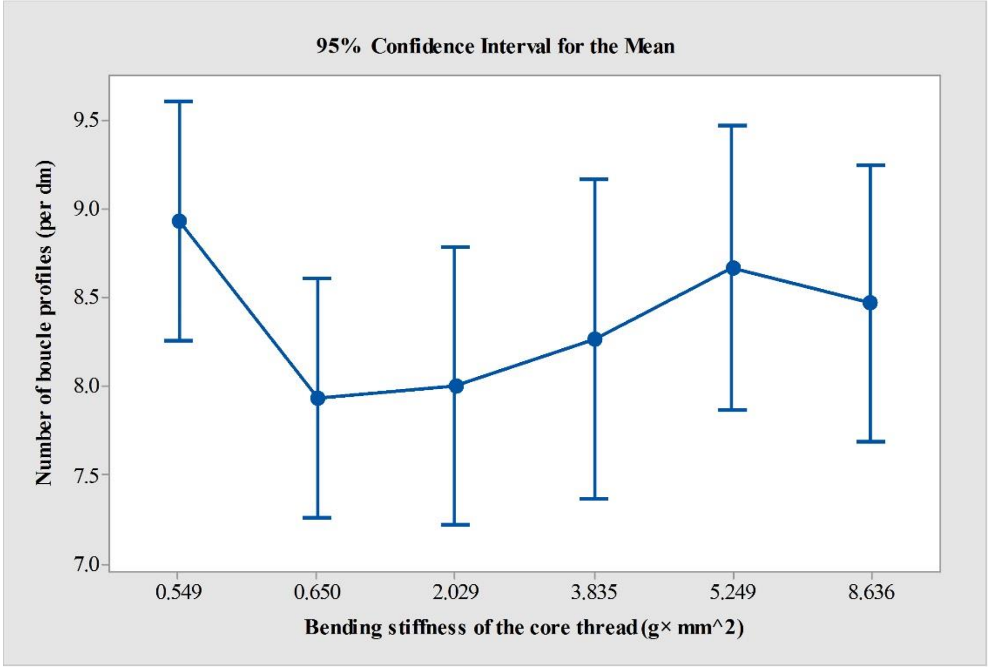


Figure 38: Interval Plot for the Influence of the Bending Stiffness of the Core Thread and the Number of Bouclé Profiles

Figure 39 shows the 95% confidence intervals for the Circularity Ratio of Bouclé Profile of the bouclé yarns. The p-value of the ANOVA testing was 0.880. Therefore, the bouclé profiles of the bouclé yarns were statistically similar in terms of their circularity.

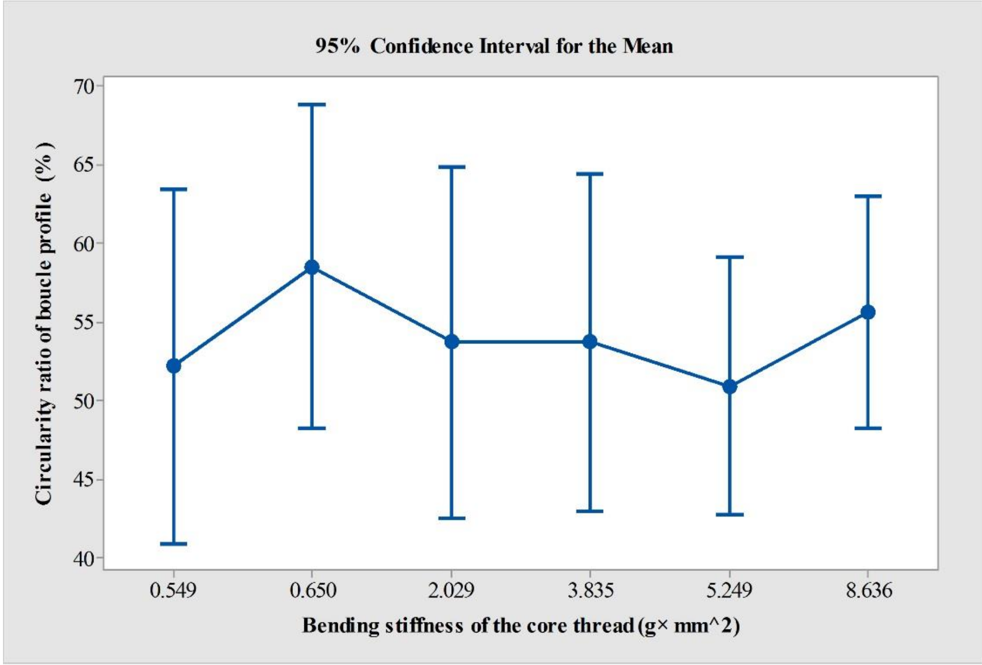


Figure 39: Interval Plot for the Effect of the Bending Stiffness of the Core Thread on the Circularity Ratio of Bouclé Profile

5.9.1 Morphology of the Bouclé Yarns

Figure 40 shows images of the bouclé yarns of this experiment. This figure shows that the bouclé yarns were similar in structure but different in colour. This is because the input yarns were different in colour. However, although the input threads were different in the type of material and bending stiffness, as given in Section 3.11, the bouclé yarns had similar morphological appearance. This is because the fancy profiles of yarns 1, 2, 3, 4, 5 and 6 had bouclé profiles, semi-bouclé profiles, sigmoidal sections, a few loops and a few wavy sections. Additionally, the size and number of the bouclé and semi-bouclé profiles appear to be similar. Although the section of yarn 4 initially appear to show a lower number of profiles than the other yarns, this section, in reality, has 6 bouclé profiles but 2 of them are standing horizontally underneath the lens of the camera used to take the photos.

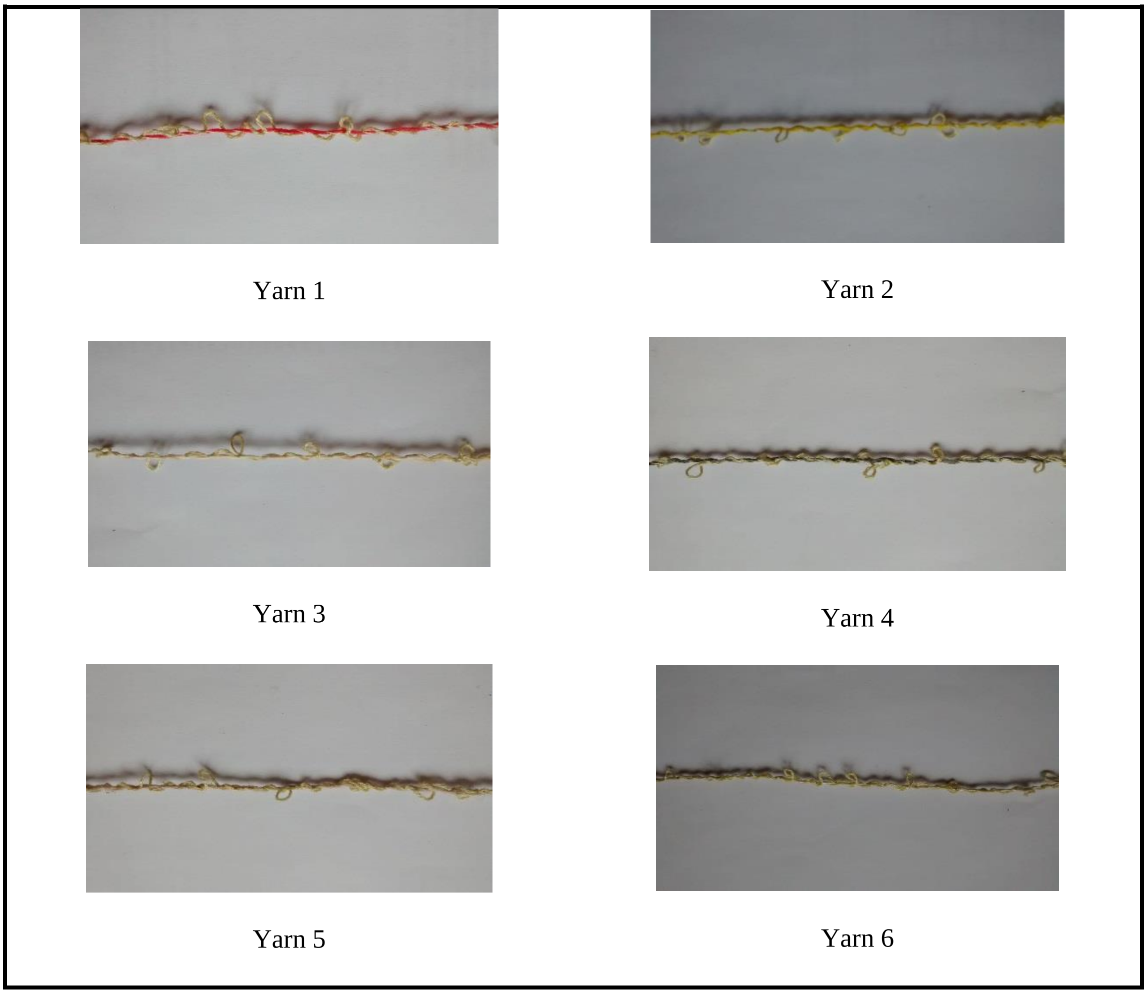


Figure 40: Images of the Bouclé Yarns Made to Test the Influence of the Bending Stiffness of the Core thread on the Structure of Bouclé Yarn

5.9.2 Conclusion

The bending stiffness of the core thread did not affect the structure of multi-thread bouclé yarn. The differences observed between those yarns may be attributed to the machine vibration and to random variation.

5.10 Testing the Influence of the Overfeed Ratio of the Effect Thread on the Structure of Bouclé Yarn

5.10.1 Morphology and Appearance of the Bouclé Yarns

The bouclé yarns made are shown in Figure 41.

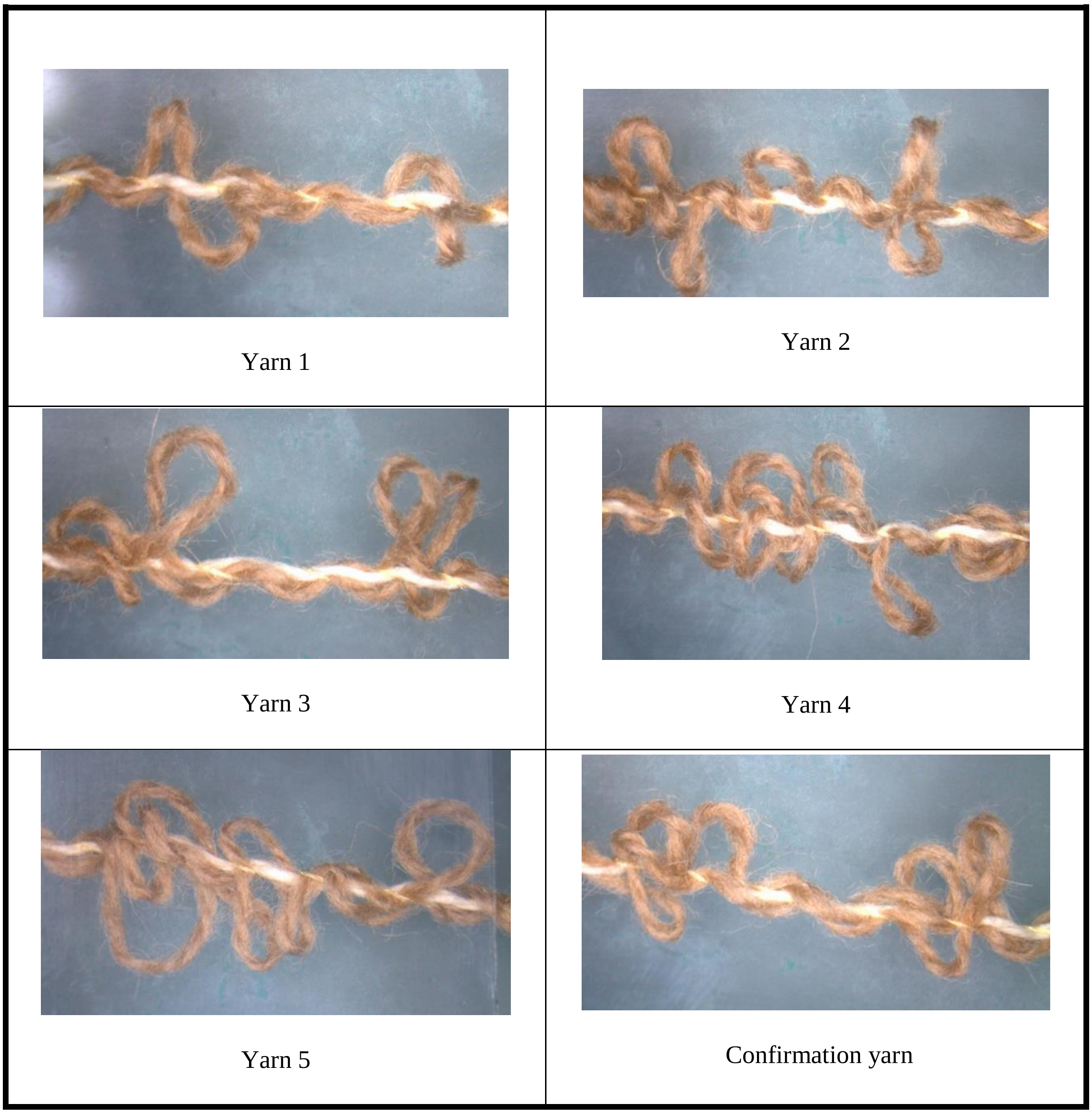


Figure 41: Images of the Fancy Yarns Made to Test the Influence of the Overfeed Ratio of the Effect Thread on the Structure of Bouclé Yarn

Figure 41 shows that all the fancy yarns made had bouclé profiles, semi-bouclé profiles, a few waves and sigmoidal sections and a minority of loops. However, the most dominate type of profile was bouclé profiles, so those fancy yarns were bouclé yarns. Figure 41 also shows that the number of bouclé profiles increased from yarn 1 until yarn 5. Further, the bouclé and semi-bouclé profiles started to cluster in yarns 4 and 5. Furthermore, the bouclé profiles became larger when making yarn 2 until yarn 5.

5.10.2 Numerical Results

Table 38 gives the results of testing the bouclé yarns of this experiment. The data of this table were used to generate Figure 42, Figure 43, Figure 44 and Figure 45. Since the bouclé and semi-bouclé profiles clustered in yarn 4 and yarn 5, the Shape Factor of Fancy Yarn (ShF) did not represent the visual and aesthetic Absolute Fancy Bulkiness of Bouclé Profiles. This is because of the irregular distribution of the bouclé profiles along the bouclé yarn axis.

Table 38: The Results of Testing the Influence of the Overfeed Ratio of the Effect Thread on the Structure of Bouclé Yarn

Cone of Bouclé Yarn	**Overfeed Ratio η %**	**Size of Bouclé Profile mm^2**	**SD of the Size mm^2**	**Circularity Ratio of Bouclé Profile %**	**SD of the Circularity Ratio %**	**Number of Bouclé Profiles dm^{-1}**	**SD of the Number dm^{-1}**	**ShF $mm^2\ dm^{-1}$**
Cone 1	180	13.57	3.17	60	17	11.93	2.25	161.94
Cone 2	200	16.28	4.03	55	14	13.40	1.88	218.11
Cone 3	220	22.18	8.15	53	17	15.73	3.13	348.82
Cone 4	240	29.85	11.17	50	18	15.93	1.83	475.52
Cone 5	260	32.66	16.79	56	16	16.40	2.77	535.61
Confirmation Cone	210	19.77	5.64	57	20	15.33	0.90	303.04

Regarding the Size of Bouclé Profile, Figure 42 indicates that the higher the overfeed ratio the larger the bouclé profiles and the higher the levels of variability of the size of these profiles. These relationships were linear and the regression equations were:

$$Size\ of\ Bouclé\ Profiles\ = -34.0 + 0.259 \times \eta\,\% \tag{5.10}$$

$$SD\ of\ Size\ = -6.254 + 0.6511 \times Size\ of\ Bouclé\ Profile \tag{5.11}$$

Where the mean value and standard deviation of the Size of Bouclé Profile were measured in mm^2 and η (%) is the (theoretical) overfeed ratio. Its value should be between 175 ~ 235% in order to avoid the formation of non-bouclé profiles or clusters from bouclé profiles.

The results of the ANOVA testing indicated that regression model 5.10 was significant at a confidence level 99% and the p-value was 0.002. Regression model 5.11 also was significant at a confidence level 99% and the p-value was 0.007. Regression model 5.11 was useful to predict the level of variation associated with the mean value of the Size of Bouclé Profile.

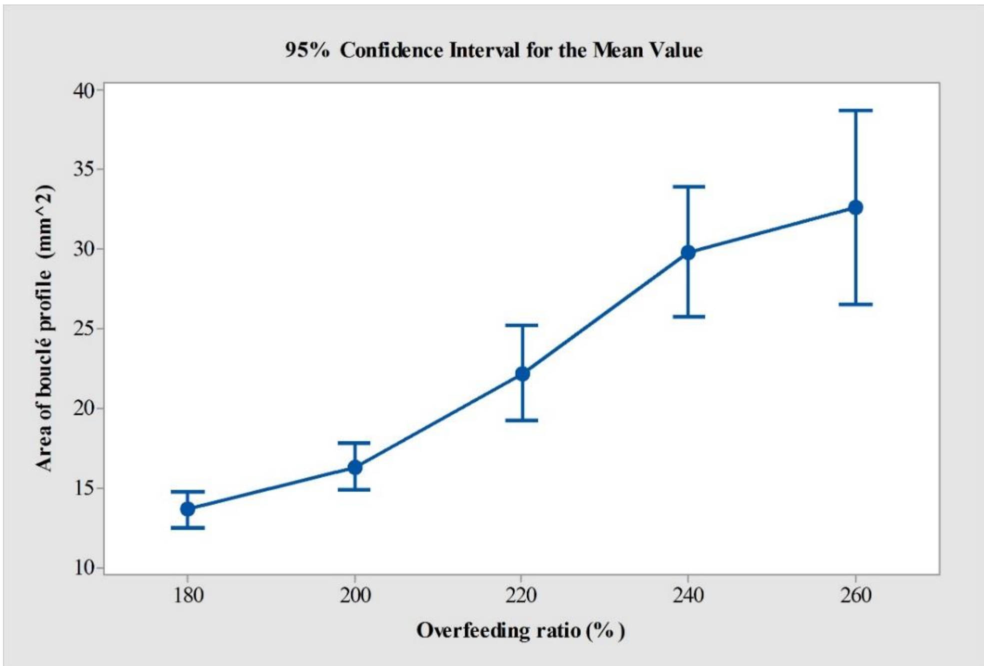


Figure 42: The Relationship between the Overfeed Ratio and the Size of Bouclé Profile

The results of the Size of Bouclé Profile were explained by considering the First Spinning Zone on the hollow-spindle spinning machine. The geometry of the effect-thread helices on this zone had a direct relationship with the structure of the resultant multi-thread fancy yarn (Section 4.9). It was found that increasing the overfeed ratio led to an increase in the width of the effect-thread helices formed in this zone (Section 5.3). This in turn results in larger fancy profiles including bouclé profiles.

The trend obtained for the variation in the Size of Bouclé Profile was attributed to several reasons:

(1) Variability of geometry of the effect-thread helices in the First Spinning Zone may result in variation in the size and number of fancy profiles including bouclé profiles.

(2) The high levels of the supply speed needed to produce high overfeed ratios may result in high levels of vibration in the machine parts. Furthermore, the vibration transmitted from the machine to the threads in the First Spinning Zone is normally higher than that of the machine parts. Consequently, it may cause unstable movement of the threads and unstable helices and spinning geometry. These in turn can severely affect the formation of fancy profiles during the formation of the intermediate product within the hollow spindle. However, a stiff effect thread is less likely to conform to the machine vibration than a softer effect thread. Therefore, using a relatively stiff effect thread may suffice to reduce the variability in the size of the profiles when raising production speeds.

(3) The irregular formation of new bouclé profiles from the other types of fancy profiles when the overfeed is increased may result in variation in the size and number of bouclé profiles (Section 4.6.3). An increase in the overfeed ratio may increase the height of all types of fancy profile on the bouclé yarn. Consequently, it may create new bouclé profiles, and increase the size of the profiles already available on the fancy yarn.

In terms of the Number of Bouclé Profiles, Figure 43 indicates that as the overfeed ratio increased, so did the number of bouclé and semi-bouclé profiles. This relationship was a simple, linear regression model as follows:

$$Number\ of\ Bouclé\ and\ Semi-bouclé\ Profiles\ = 2.06 + 0.0574 \times \eta\,\% \qquad (5.12)$$

Regression model 5.12 was significant at a confidence level 99% and the p-value of the ANOVA testing was 0.017. The variability of this bouclé yarn property, as given in Table 38, did not have any clear trend.

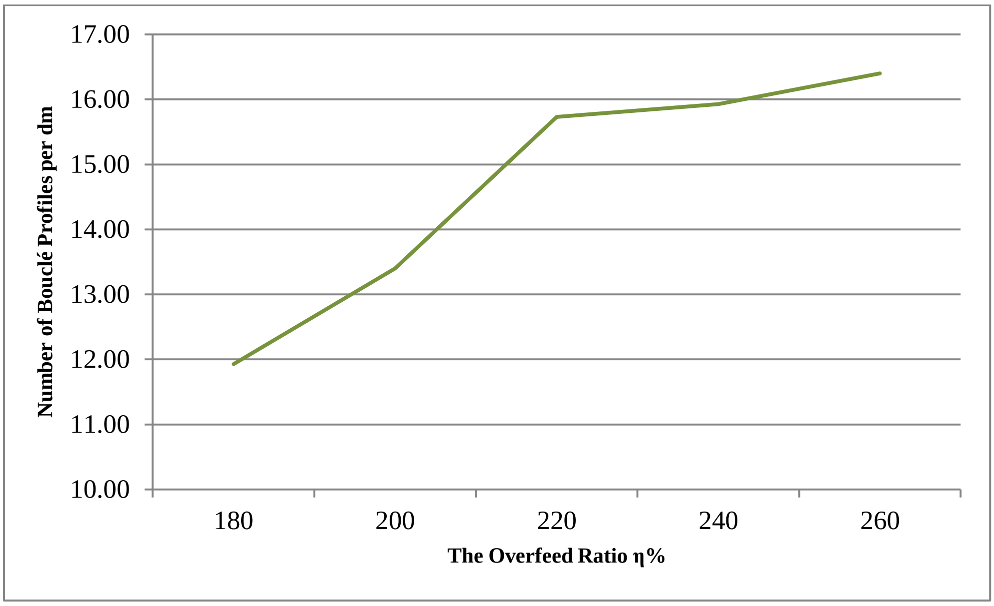


Figure 43: The Relationship between the Overfeed Ratio and the Number of Bouclé and Semi-bouclé Profiles

Increasing the overfeed ratio created more bouclé profiles because it provided sufficient lengths of the effect threads to some of the arcs, waves and sigmoidal sections of the bouclé yarn to grow larger (Section 4.6.3). Therefore, the heights of those sections increased to be approximately similar to the heights of the bouclé profiles already available on the fancy yarn. As a result, new bouclé profiles have formed at the expense of a reduction in the number of the arcs, waves and sigmoidal sections. However, such an increase in the height of those profiles was not regular. Further, there was also an increase in the height of the bouclé profiles already available on the fancy yarn. Subsequently, the sizes of the old and the new bouclé profiles were not equal and not consistent. As a result, an increase of the variation in the size of the profile has also happened with rising the overfeed ratio.

With regard to the Absolute Fancy Bulkiness of Bouclé Profiles, Figure 44 was instructive.

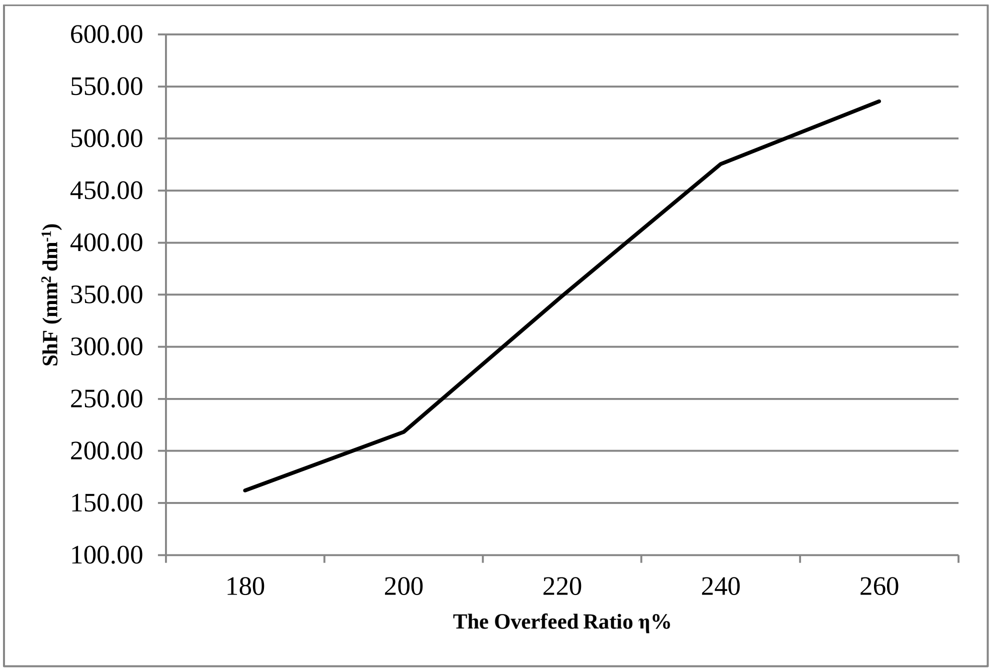


Figure 44: The Relationship between the Overfeed Ratio and the Shape Factor of Bouclé Yarn

This figure shows that the Shape Factor of Bouclé Yarn (ShF) increased with the overfeed ratio linearly according to the relationship:

$$ShF = -757 + 5.02 \times \eta\ \% \qquad (5.13)$$

Where the ShF is measured in $mm^2\ dm^{-1}$.

Regression model 5.13 was theoretically significant at a confidence level 99% and the p-value of ANOVA was 0.001. The increase in the value of the Shape Factor of Bouclé Yarn related to the increases in both the number and area of the bouclé profiles with the overfeed ratio. Lower values of overfeed ratio made bouclé yarns with a relatively low amount of absolute fancy bulkiness.

With respect to the Circularity Ratio of Bouclé Profile (CR), Figure 45 showed that increasing the overfeed ratio reduced the CR of the profiles.

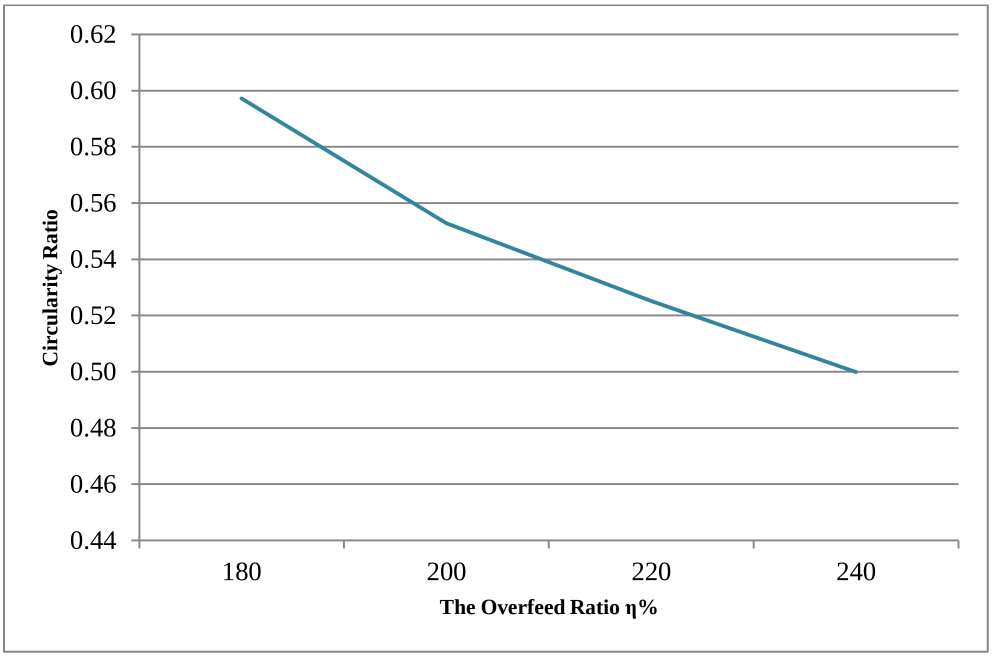


Figure 45: The Relationship between the Overfeed Ratio and the Circularity Ratio of Bouclé Profile

The relationship was a regression line as follows:

$$Circularity\ Ratio\ of\ Boucl\acute{e}\ Profile\ (\%) = 88.1 - 0.160 \times \eta(\%) \qquad (5.14)$$

This regression model was significant at a 99% confidence level and the p-value of the ANOVA testing was 0.017. This relationship was important because the previous experimental work did not indicate any clear relationship between the circularity ratio and any of the factors studied.

The reduction in the circularity ratio of the profiles was related to changes to the height of the bouclé profiles, due to the increase in the overfeed ratio, which made them larger and longer. Since long profiles are more deviated from the circular shape than the original profiles, the circularity ratio decreased in this experiment. The surge in the circularity ratio when the overfeed ratio was 260% was ignored in the analysis because the bouclé profiles had deformed. This happened because many bouclé profiles clustered in groups along the final yarn. Such clustering forced the bouclé profiles to impose mutual pressure on each other, especially when competing for position within the clusters.

It is worth mentioning that when considering the case of a fancy gimp yarn, a fancy wavy yarn or an overfed fancy yarn, the increase in the overfeed ratio may increase the value of circularity ratio of the profiles. This is because the fancy profiles of those types of fancy yarn have an elongated shape. Consequently, the increase in the overfeed ratio may keep increasing their circularity ratio until the fancy profiles become bouclé profiles. However, further increases in the overfeed ratio may force the bouclé profiles to assume an elongated shape; thus, reducing their circularity ratio.

5.10.3 Testing the Regression Models

The regression models 5.10, 5.11, 5.12, 5.13 and 5.14 were tested by making a confirmation bouclé yarn. The setting of the machine for this yarn was given number 6 in Table 9. The results of the confirmation test are given in Table 39 which shows that the agreement between the real values and the predicated values was high. Therefore, those regression models can be used to predict the characteristics of bouclé yarns with reasonable accuracy.

Table 39: The Results of Testing the Regression Models of Importance of the Overfeed Ratio to the Structure of Bouclé Yarn

Fancy Yarn Property	**Predicted Value (P)**	**Actual Value (A)**	**% Deviation from the Predicted Value (A-P)× 100/P**
Size of bouclé profiles, mm^2	20.39	19.77	-3
Standard deviation of the size, mm^2	6.62	5.64	Not required
Number of bouclé profiles, dm^{-1}	14.03	15.33	9.2
ShF, mm^2 dm^{-1}	297.2	303.04	1.96
Circularity ratio	55 %	57 %	3.63

5.10.4 Conclusions

- The increase in the overfeed ratio made proportional increase to the size of bouclé and semi-bouclé profiles. This relationship was linear and significant at a 99% confidence level.
- The increase in the overfeed ratio made proportional increase to the number of bouclé and semi-bouclé profiles. This relationship was linear and significant at a 99% confidence level.
- The increase in the overfeed ratio made proportional increase to the Shape factor of Bouclé Yarn. This relationship was linear and significant at a 99% confidence level.
- The increase in the overfeed ratio made proportional decrease to the circularity ratio of the profile. This relationship was linear and significant at a 99% confidence level.
- The variability of the size of bouclé profiles had was proportional to the mean value of the size of the bouclé profile. This relationship was significant at a 99% confidence level.

5.11 Assessing the Influence of Number of Wraps on the Structure and Quality Parameters of Bouclé Yarn

5.11.1 Morphology and Appearance of the Bouclé Yarns

Images of the bouclé yarns made are shown in Figure 46. This figure shows that the yarns made had bouclé profiles, wavy sections, sigmoidal sections, and semi-bouclé profiles. Therefore, the yarns were bouclé yarns. Moreover, the yarn structure became tighter and more compact and the bouclé profiles became smaller the starting from yarn 1 until yarn 7. Additionally, the number of bouclé profiles increased when observing the bouclé yarns in the same order.

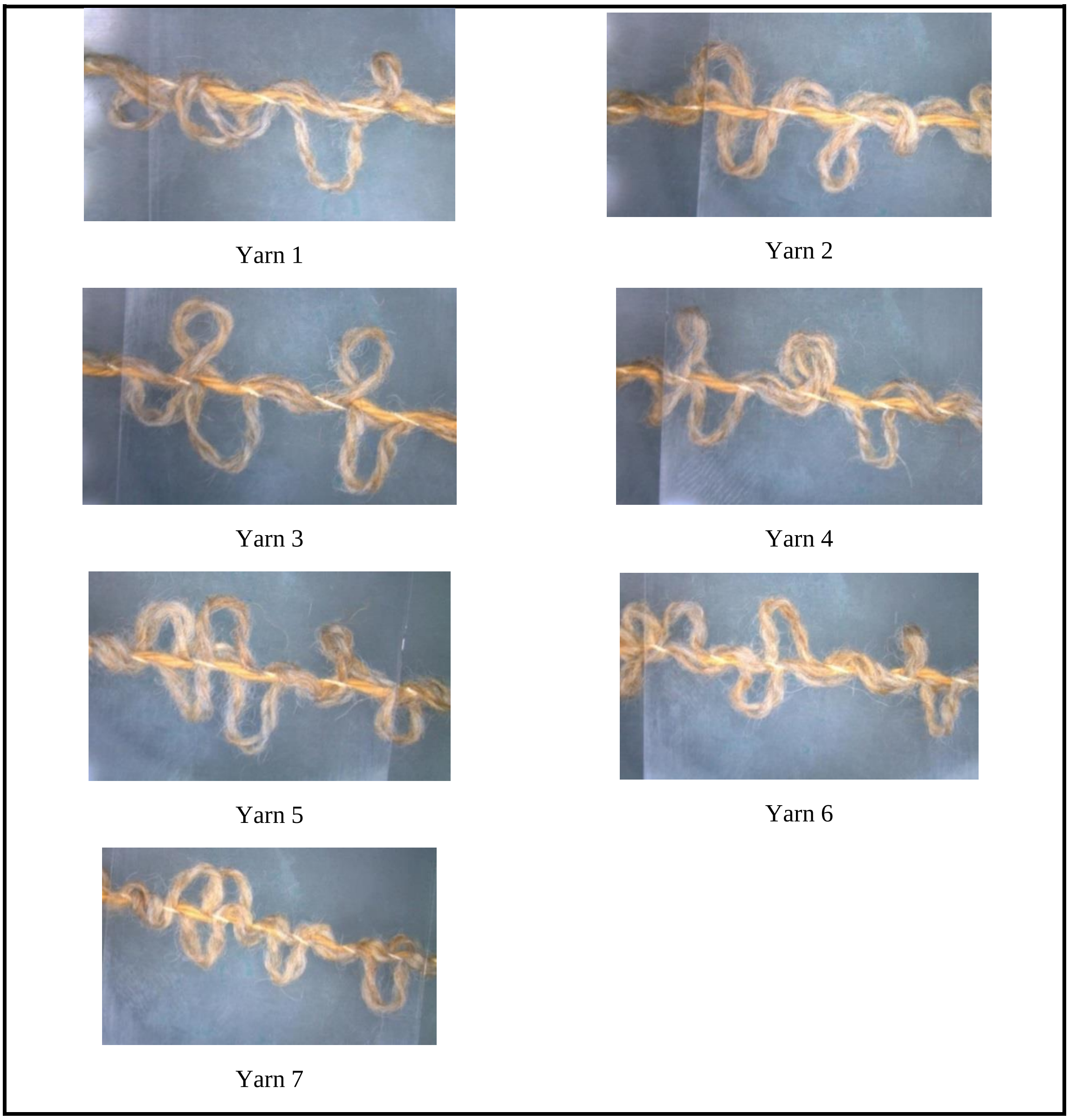


Figure 46: Images of the Bouclé Yarns Made to Test the Effect of the Number of Wraps on the Structure of Bouclé Yarn

5.11.2 Numerical results

The data collected from the yarns are presented in Table 40 and they were used to make Figure 47, Figure 48 and Figure 49.

Table 40: The Results of Testing the Effect of the Number of Wraps on the Structure of Bouclé Yarn

Bouclé Yarn	W Theoretical) wpm	W (Measured) wpm	SD of W wpm	Size of Bouclé Profile mm^2	SD of the Size mm^2	Number of Bouclé Profiles dm^{-1}	SD of the Number dm^{-1}	ShF mm^2 dm^{-1}
yarn 1	160	184	6.5	21.64	7.62	13.40	1.68	289.99
yarn 2	170	192	8.4	17.76	7.91	13.93	2.08	247.33
yarn 3	180	198	16.8	18.63	5.28	14.07	1.48	262.08
yarn 4	190	204	5.5	16.96	4.17	14.07	2.53	238.60
yarn 5	200	216	16.4	16.31	4.26	13.80	2.04	225.04
yarn 6	210	223	15.7	15.15	4.41	14.80	2.48	224.20
yarn 7	220	233	4.5	14.09	2.90	13.38	2.02	188.47
Confirmation yarn	230	242	14.4	15.14	3.17	14.73	3.17	223.07

Figure 47 indicates that increasing the number of wraps (wpm) reduced the area of the bouclé profiles (mm^2). This relationship represented a linear regression model:

$$Size\ of\ Boucl\acute{e}\ Profile = 37.7 - 0.108 \times Number\ of\ Wraps \tag{5.15}$$

This regression model was significant at a 99% confidence level and the p-value of the ANOVA testing was 0.002.

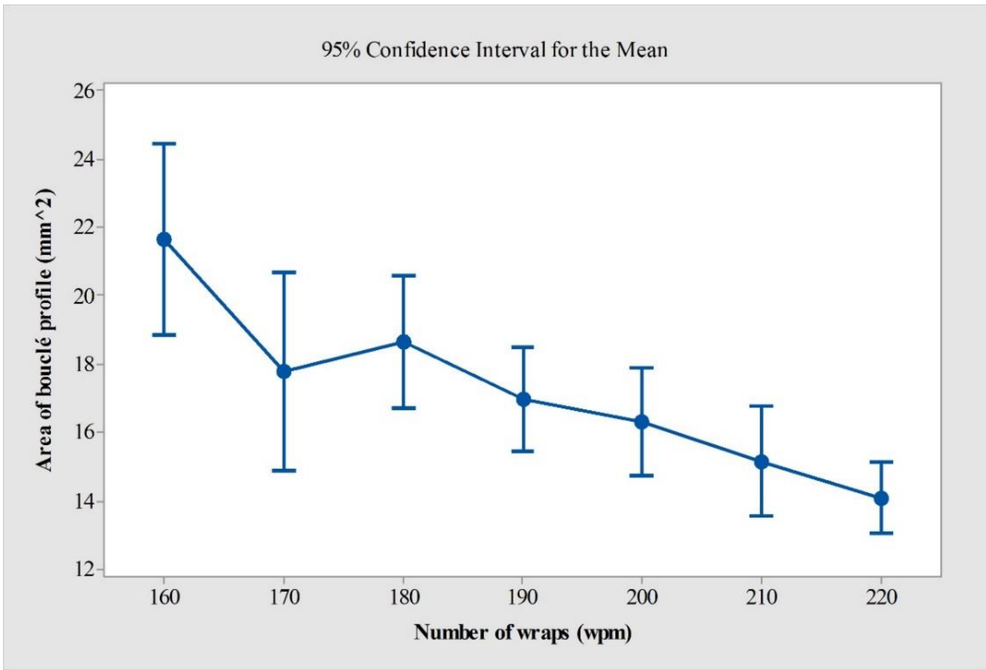


Figure 47: The Relationship between the Size of Fancy Profile and the Number of Wraps

Figure 48 shows that high numbers of wraps result in low variation in the size of the profiles, while low numbers of wraps allowed for more variation in the size of the profiles. Consequently, high number of wraps reduced the average size of bouclé profiles and improved their consistency. The decrease in the Size of Bouclé Profile, even though the overfeed ratio (η) was fixed, meant that the sigmoidal sections of the bouclé yarns became bulkier with wider diameters[21]. These results were explained as follows:

When the number of wrap increases, the distance between successive wraps of the binder decreases proportionally. Therefore, the width of base of the profiles becomes narrow while their circumferences become short. Consequently, the area of the profiles becomes small. Since the area of bouclé profile defines its size, the Size of Bouclé

[21] This type of change in the appearance and texture of multi-thread fancy yarn is normally reflected through different values of the Relative Shape Index of Fancy Yarn (RSI). Accordingly, an array of an ascending or descending order for the Relative Fancy Bulkiness of those fancy yarns may be obtained.

Profile becomes small. Furthermore, the arcs, waves and sigmoidal sections of the bouclé yarn receive the lengths of the effect threads that were supposed to make larger bouclé profiles. Eventually, those arcs, waves and sigmoidal sections become bulky and have wide diameters. Further, the extra wraps added to the bouclé yarn reduce the distance available for the legs of the bouclé profiles to project out of the bouclé yarn surface. Consequently, reductions in the variability of the size of the profiles happen by raising the number of wraps.

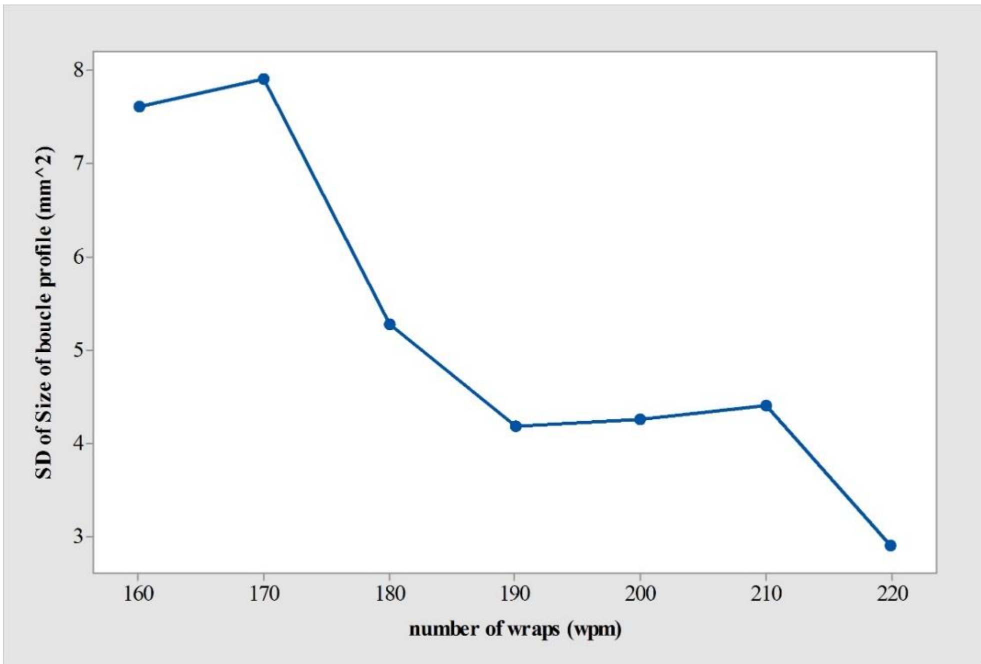


Figure 48: Relationship between the Variability of the Size of Bouclé Profile and the Number of Wraps

With respect to the Number of Bouclé Profiles, the data in Table 40 did not indicate any obvious or remarkable change in the Number of Bouclé Profiles due to the changes of the number of wraps, over the range of wraps used. Moreover, no obvious change happened to its variability; thus, it was thought to be a random variation.

Figure 49, which accounts for the Absolute Fancy Bulkiness of Bouclé Profiles, shows that, when the number of wraps was raised, the Shape Factor of Fancy Yarn (ShF) decreased. This reduction was related to the reduction in the Size of Bouclé Profiles when the number of wraps was raised. The ShF was 290 $mm^2\ dm^{-1}$ for W=160 wpm; but it was as low as 190 $mm^2\ dm^{-1}$ for W= 220 wpm. A 100 $mm^2\ dm^{-1}$ reduction in the Absolute Fancy Bulkiness of Bouclé Profiles was a large change in the quality of the bouclé yarns for a 60 wpm change in the number of wraps. The following linear regression equation was obtained:

$$ShF\ of\ the\ Boucl\acute{e}\ Yarn\ = 503\ -\ 1.39\ \times\ Number\ of\ Wraps \qquad (5.16)$$

This model was significant at a 99 % confidence level and the p-value of the ANOVA testing was 0.002.

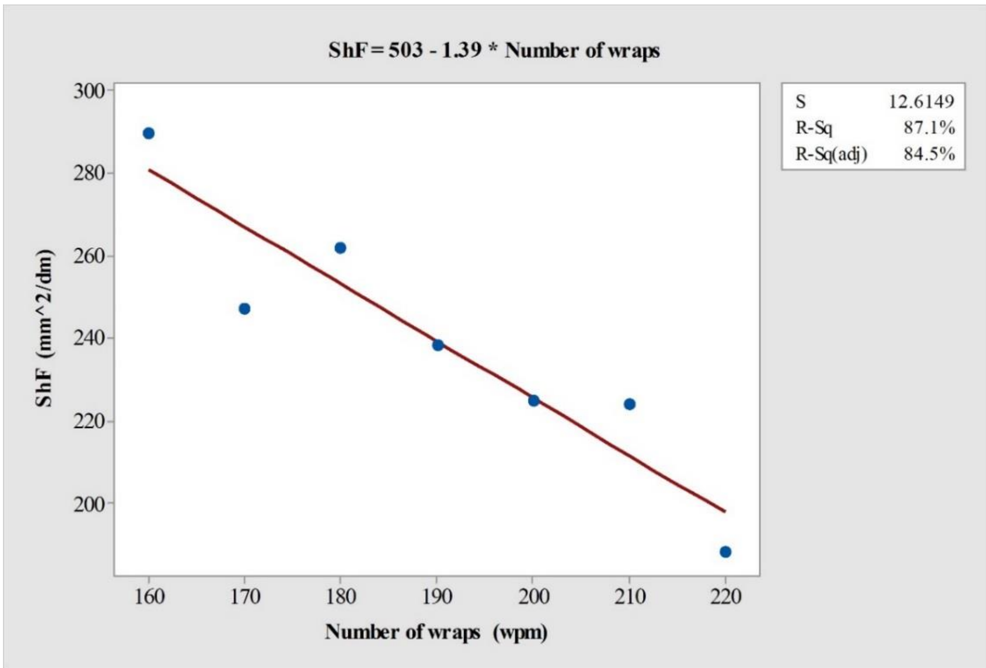


Figure 49: The Relationship between the Absolute Fancy Bulkiness of Bouclé Yarn and the Number of Wraps

Table 40 Shows that there were differences between the number of wraps set using the machine (the theoretical number of wraps), and the real number of wraps which received by the bouclé yarns. However, there was a linear, significant relationship between those numbers of wraps as given in Figure 50 because the p-value of this relationship was 0.000.

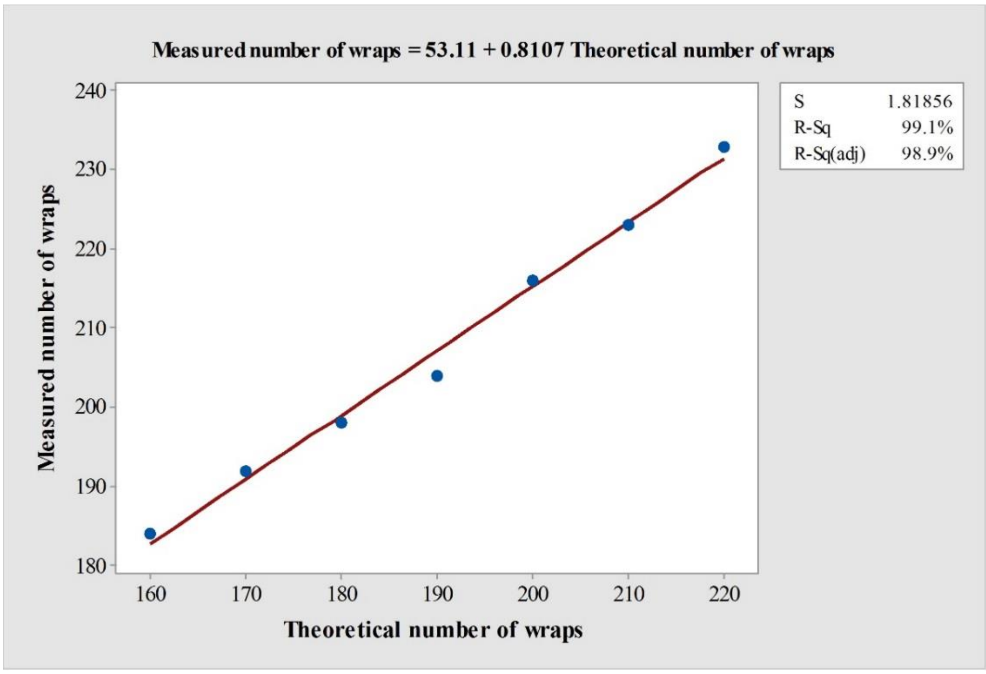


Figure 50: Relationship between the Theoretical Number of Wraps and the Actual Number of Wraps

It is worth mentioning that the trends resulted in this experiment were all simple regression models. However, the regression lines were not perfectly linear in Section 5.6. The first reason for these differences is related to the number of effect threads used. There were two effect threads in this experiment while only one effect thread in the experiment of Section 5.6. The second difference is the high overfeed ratio for the two effect threads in this experiment, i.e. 200 %, in comparison with only 166% in the experiment in Section 5.6. These differences may account for significant changes in the nature of motion of the threads within the First Spinning Zone. For example, when considering the case of two effect threads, there is the possibility of interactions between them while advancing in the First Spinning Zone. Such interactions may be impact, friction, slippage and/or pressure. Such interactions may bring about modifications to the threads geometry in the First Spinning Zone. However, such interactions are not expected to happen in the case of using only one effect thread. This is because the thread assumes a helical configuration if the rotational speed is suitable and sufficient.

5.11.3 Testing the Regression Models

In order to test the regression models 5.15 and 5.16, a bouclé yarn was made on a confirmation cone. The machine setting number 8 given in Table 10 (given in Section 3.12) was used to make the confirmation yarn, while the results of the tests are given in Table 40. The results of a comparison between the predicted values and the actual values are given in Table 41. Clearly, all the values which resulted for the confirmation yarn were higher than those predicted by the models. Further, the deviations exceeded the accepted limit of 15 %. The reasons for this deviation may have been the variability that is related to the process of manufacture on the hollow-spindle system and the variation that is originating from the machine itself.

Table 41: Testing the Regression Models

Regression Model of	**Predicted Value (P)**	**Actual Value (A)**	**Deviation from Predicted Value (%) (A-P)× 100/P**
Size of Bouclé Profile, mm^2	12.86	15.14	17.72
ShF, mm^2 dm^{-1}	183.3	223.07	21.69

5.11.4 Conclusions

- The increase in the number of wraps of the binder of the bouclé yarns decreased the Size of Bouclé Profiles significantly, but improved their consistency in size (i.e. lower variation).
- The increase in the number of wraps also made significant reductions to the Absolute Fancy Bulkiness of Bouclé Profiles.

- The changes in the number of wraps did not alter the Number of Bouclé Profiles.
- Although statistically significant relationships were obtained, the regression models were not sufficiently accurate to predict the structure and quality of bouclé yarn.
- The variability of the hollow-spindle machine must be investigated since it may affect the quality of the resulting bouclé yarns.

5.12 The Relationships between Structural Parameters and Quality Parameters of Bouclé Yarn

The material, the settings of the machine, the experimental design and the structural parameters used for this experiment are given in Section 3.14. Images of the yarns made are shown in Figure 51. This figure shows that the different settings of the machine used resulted in profound differences between the fancy yarns made. Further, not all of those fancy yarns can be called bouclé yarns. Using the subjective method of assessment and based on Figure 51, it is thought that:

- The fancy yarns which may be called bouclé may be the yarns made at Trials 1, 3, 4, 5, 6 because those yarns appear to have bouclé profiles, semi-bouclé profiles, and regular wavy and sigmoidal sections.
- The fancy yarn which may be called semi-bouclé may be the yarn of Trials 7 because it appears to have semi-bouclé profiles and regular wavy and sigmoidal sections.
- The yarns of Trials 2, 8, 9 may be called overfed fancy yarns due to the extremely large fancy profiles and irregular wavy and sigmoid sections.

Fancy yarn of Trial 1

Fancy yarn of Trial 2

Fancy yarn of Trial 3

Fancy yarn of Trial 4

Fancy yarn of Trial 5

Fancy yarn of Trial 6

Fancy yarn of Trial 7

Fancy yarn of Trial 8

Fancy yarn of Trial 9

Figure 51: Images of the Bouclé Yarns Made to Map the Relationship Between the Structural Parameters and the Quality Parameters of Fancy Yarn

To define the name and quality of those fancy yarns more accurately, their structure was assessed objectively using the objective method (as given in Section 3.1.1). So, those yarns were tested and the results are included in Table 42. Further, their quality parameters were tested for normality at the significance level $\alpha = 0.10$. Due to its importance, these results were analysed using the Structural Ratio of Multi-thread Fancy Yarn instead of the traditional analysis of experimental designs using a response table or Minitab.

It was found that the Numbers of Fancy Profiles (including bouclé and semi-bouclé profiles) for yarns 1, 3, 4, 5, 7, 8 and 9 followed normal distributions; but that for yarns 2 and 6 did not. Additionally, the Size of Fancy Profile (including bouclé and semi-bouclé profiles) for yarns 1, 3, 4 and 5 followed normal distributions; but that for yarns 2, 6, 7, 8 and 9 did not. Further, yarns 2, 6, 7, 8 and 9 had high variability of the structure because the CV% values for the Size of Fancy Profile was between 35.7% and 70.8 %. Although the CV is high, the yarn structure under consideration had both bouclé and semi-bouclé profiles which are similar to each other, but not exactly the same. So, in their nature their variability is high; not to mention the variability of the manufacturing process of doubled fancy yarns on hollow-spindle machines. Furthermore, in this particular experiment the CV% of bending stiffness of the effect threads (B_e) was 40.9 %; thus, a CV ≈ 40% of Size of Fancy Profile was as the most suitable criterion to judge the quality of the bouclé and the other fancy profiles. Any yarn which exceeded the CV=40%, was labelled "irregular overfed fancy yarn". Therefore, values of the Shape Factor of Fancy Yarn and the Relative Shape Index of Fancy Yarn were only calculated for the fancy yarns which had CV<40%. Based on this criterion, only fancy yarn 7 had an acceptable variability, amongst yarns 2, 6, 7, 8 and 9, because its CV=35.7% < 40 %; while the variability of the fancy yarns 2, 6, 8 and 9 were not acceptable, i.e. those yarns had inferior quality. Furthermore, it was observed that the Structural Ratio of Multi-thread Fancy Yarn for yarns 2, 6, 8 and 9 were low.

Table 42: The Results which Shows Relationship between the Structural Parameters and the Quality Parameters of Fancy Yarn

Fancy Yarn of randomised-order	W (wpm)	η	SR (wpm)	Size of Profile (mm^2)	SD of Size (mm^2)	CV% of Size	Number of Profiles (m^{-1})	SD of the Number of Profiles (m^{-1})	ShF ($mm^2\ m^{-1}$)	Linear Density (tex)	RSI=ShF/T_{tex} ($mm^2\ m^{-1}\ tex^{-1}$)	Fancy Yarn Designation
Trial 1	220	250%	0.88	20.87	7.09	33.96	21.6	3.8	450.792	809.97	0.556	bouclé
Trial 2	190	250%	0.76	25.46	12.24	48.06	16.8	2.9	not necessary	not necessary	not necessary	Overfed or irregular bouclé
Trial 3	190	210%	0.9	20.34	7.93	38.96	14.2	3	288.828	721.88	0.4	bouclé
Trial 4	190	180%	1.05	15.16	4.08	26.9	11.33	1.9	171.762	642.5	0.267	bouclé
Trial 5	220	210%	1.05	13.29	2.4	18.04	16.47	3.18	218.886	714.77	0.306	bouclé
Trial 6	160	210%	0.76	32.96	13.91	42.2	10.27	2	not necessary	not necessary	not necessary	Irregular overfed
Trial 7	220	180%	1.22	14.62	5.23	35.74	5.2	1.26	76.024	660.61	0.115	Semi-bouclé or compact bouclé
Trial 8	160	180%	0.89	29.65	14.16	47.76	7.6	1.5	not necessary	not necessary	not necessary	Irregular overfed
Trial 9	160	250%	0.64	37.84	26.82	70.87	6	2.13	not necessary	not necessary	not necessary	Irregular overfed

Using Figure 52, it was observed that when the Structural Ratio of Multi-thread Fancy Yarn (SR) was increased, the Size of Fancy Profiles was decreasing. A similar result was observed for the standard deviation (SD) of the Size of Fancy Profile. Moreover, it was concluded that the reduction in the variation of Size of Fancy Profile was related to the reduction in the mean value of the same parameter. It is important to mention that the high values of the mean value and the standard deviation of the Size of Fancy Profile which corresponded to SR=0.89 wpm indicated that the number of wraps for this trial was inappropriate. Therefore, the two visible peaks in Figure 52 were useful to indicate the appropriateness of selecting the levels of the structural parameters and the process variables.

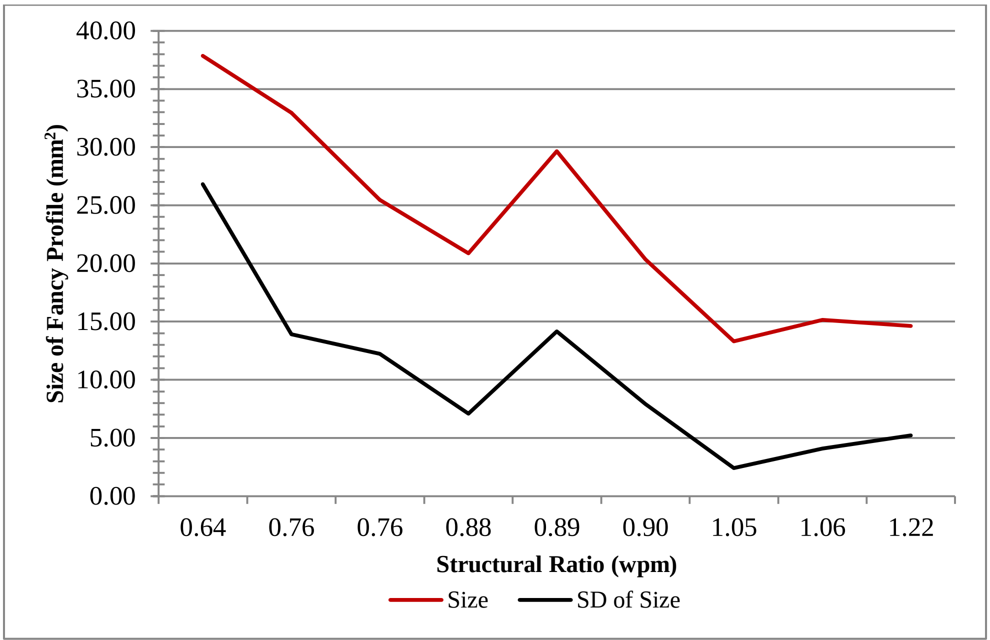


Figure 52: Influence of the Structural Ratio of Multi-thread Fancy Yarn on the Mean Value and Variability of the Size of Fancy Profile

Since the values of the Shape Factor of Fancy Yarn (ShF) can be used to account for the Absolute Fancy Bulkiness of Fancy Yarn, the bouclé yarns of this experiment were arranged in a descending order starting from yarn 1, then yarn 3, yarn 5, yarn 4 and finally yarn 7. However, since the linear densities of those bouclé yarns varied considerably, the Relative Shape Index of Fancy Yarn (RSI) should have been used, and the previous order remained the same.

Since the Structural Ratio of Fancy Yarn (SR) accounts for, and summarises, the interaction between the number of wraps and the overfeed ratio, the fancy yarns which had approximately similar values of SR were compared with each other. To do so, the fancy yarns were divided into three groups as follows:

- Group One, which comprises the fancy yarns 5 and 4. The SR for this group was 1.05 wpm;
- Group Two, which was made of the fancy yarns 2 and 6. The SR for this group was approximately 0.76 wpm; and
- Group Three, which contained the fancy yarns 1, 3 and 8 (because the SR≈0.89 wpm in average).

The fancy yarns of each group were different from each other in terms of the number of wraps, the overfeed ratio and the settings of the machine (as given in Table 11). Such differences were reflected in obtaining differences in the quality parameters and fancy bulkiness of the fancy yarns, in particular, in the values of the Shape Factor of Fancy Yarn (ShF) and the Relative Shape Index of Fancy Yarn (RSI), as given in Table 42.

With regard to Group One, Table 42 shows that fancy yarn 5 was made using higher number of wraps and the overfeed ratio than fancy yarn 4. Table 42 also shows that the fancy profiles of yarn 5 were smaller than those of yarn 4. Additionally, the variability in the Size of Fancy Profile for yarn 5 was smaller than that for yarn 4. Furthermore, the fancy yarn 5 had higher Number of Fancy Profiles per unit length than that of fancy yarn 4. These results were explained by recalling the results of the experiments in Sections 5.10 and 5.11. The results of Section 5.10 indicated that increasing the overfeed ratio resulted in large bouclé profiles with high levels of variation (Figure 53 (a)). However, the results given in Section 5.11 showed that increasing the number of wraps did the opposite with regard to the Size of Fancy Profiles (Figure 53(b)). Moreover, the results of Section 5.10 indicated that increasing the overfeed ratio increased the Number of Fancy Profiles (Figure 54). However, based on the results of Section 5.11, the number of wraps did not to affect the Number of Fancy Profiles.

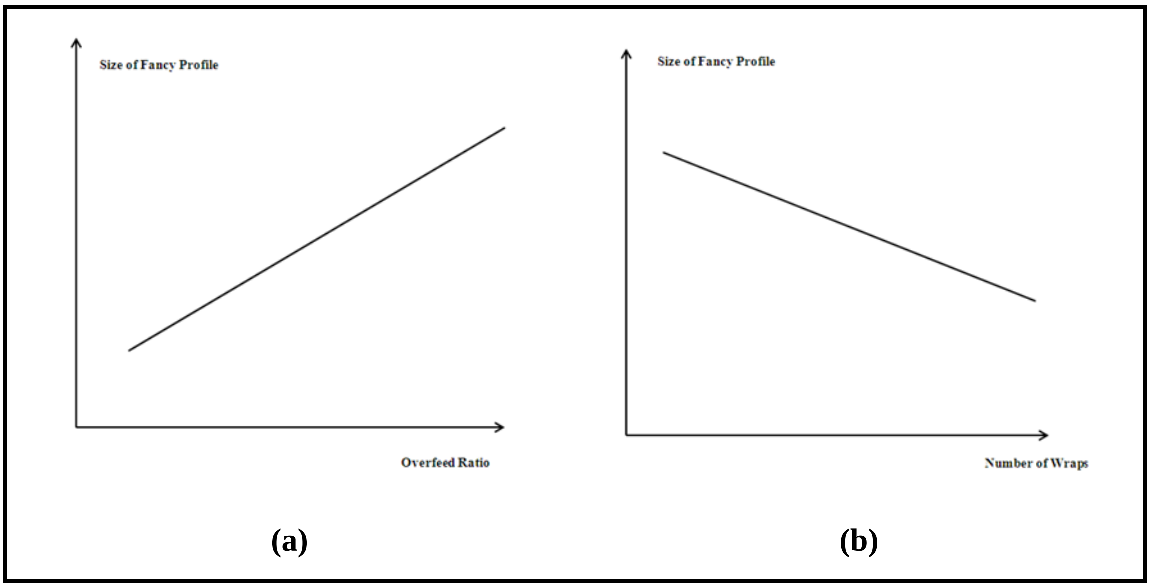


Figure 53: The Individual Influences of the Overfeed Ratio and Number of Wraps on the Size of Fancy Profile[22]

In this experiment, however, the number of wraps and the overfeed ratio were changed simultaneously and the visual trends of Figure 55 resulted for both fancy yarns 4 and 5. Figure 55 (a) indicated that the influence of the wraps on the area of the fancy profiles outdid the influence of the overfeed ratio. Therefore, the Size of Fancy Profile decreased when both the number of wraps and the overfeed ratio were increased. However, when considering the Number of Fancy Profiles, Figure 55 (b) shows that the influence of the overfeed ratio dominated, while the number of wraps remained a non-affecting factor. Subsequently, the Number of Fancy Profiles increased when both the number of wraps and the overfeed ratio were increased simultaneously. It also

[22] These plots demonstrate visual trends rather than actual regression models. Further information are given in Sections 5.10 and 5.11.

important to mention that the high rotational speed for yarn 5 had its own contribution to the results; Sections 5.4, 5.5 and 5.6 give details about such influences.

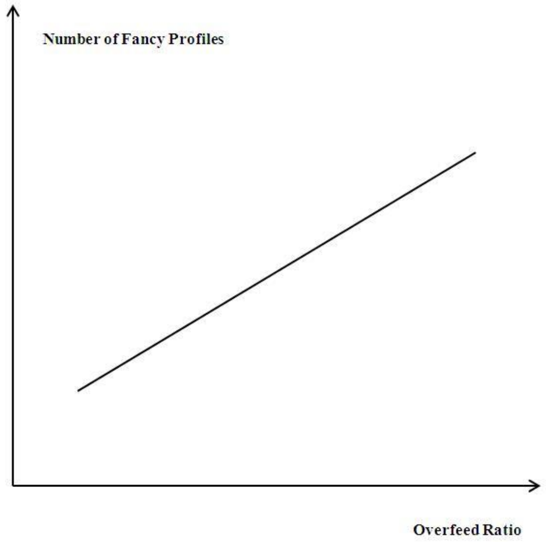


Figure 54: The Effect of the Overfeed Ratio on the Number of Fancy Profiles

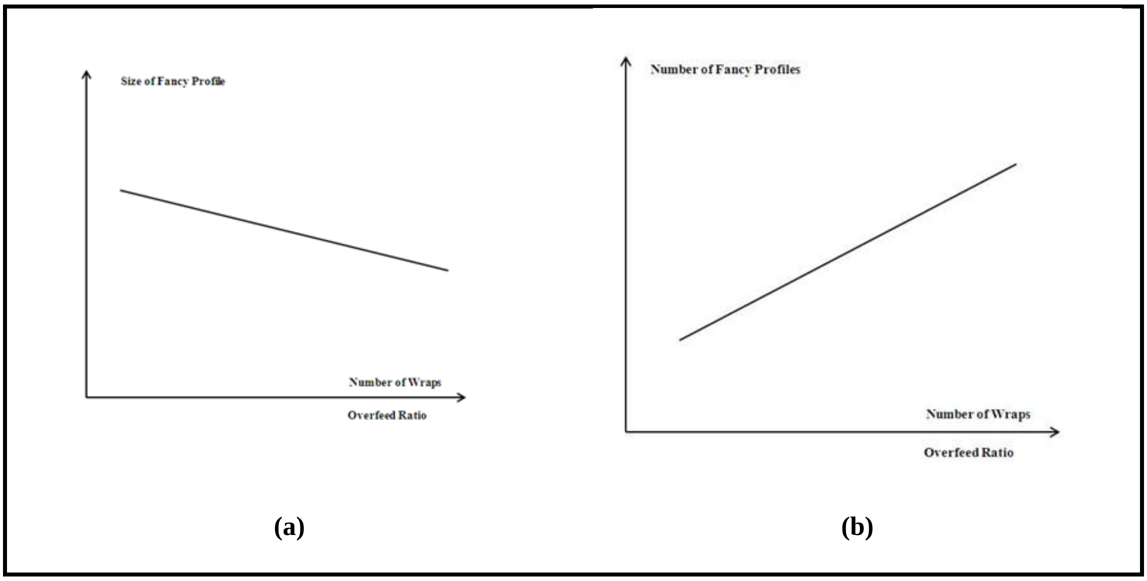


Figure 55: The Influence of Interaction of the Overfeed Ratio and Number of Wraps on the Size of Fancy Profile and the Number of Fancy Profiles

The same conclusions were also made regarding Group Two of the fancy yarns 2 and 6. Yarn 2 had higher number of wraps and overfeed ratio than yarn 6. The results in Table 42 show that the former had smaller fancy profiles with less variability than the latter. Moreover, fancy yarn 2 had more profiles per unit length than that of yarn 6. The collective influence of the simultaneous changes to both the number of wraps and the overfeed ratio, for those two fancy yarns was that higher values of the overfeed ratio increased the Number of Fancy Profiles (Figure 55 (b)), while the higher number of wraps reduced the Size of Fancy Profiles (Figure 55 (a)).

Regarding Group Three of the fancy yarns 1, 3 and 8 (SR≈0.89 wpm), the conclusions regarding the interaction effect of the number of wraps and the overfeed ratio on them were also the same as before. Increasing the overfeed ratio from 180% (for yarn 8) to 210% (for yarn 3) and then to 250% (for yarn 1) made more fancy profiles in a unit length of the fancy yarns. This is because the number of the fancy profiles increased from 7.6 profile per metre up to 14.2 profile per metre and then to 21.6 profile per metre. Furthermore, a simultaneous increase in the number of wraps from 160 wpm (for yarn 8) to 190 wpm (for yarn 3) reduced the size of fancy profiles from 29.65 mm^2 down to 20.34 mm^2. Additionally, the standard deviation of the Size of Fancy Profile decreased from 14.16 down mm^2 to 7.93 mm^2. However, a further increase in the number of wraps, in order to make yarn 1, did not affect the Size of Fancy Profile. This was because the excessively high overfeed ratio for yarn 1 prevented any further real and observable reduction in the Size of Fancy Profile. Therefore, the area of the fancy profiles reached a minimum of 7 mm^2 in this experiment. It is also worth noting that the results of those three fancy yarns were in part related to the levels of the rotational speed (which was investigated in details in Sections 5.4, 5.5 and 5.6).

Finally, with regard to the results of the two experiments that are given in Sections 5.10 and 5.11, the SR value for the first experiment (which is shown in Section 3.12) was in the range between 0.77 wpm (for yarn 5) and 1.11 wpm (for yarn 1). The low SR values, 0.77 wpm (for yarn 5) and 0.80 wpm (for yarn 4), made bouclé yarns with clustered fancy profiles. Moreover, the SR for the second experiment as shown in Section 3.13 was in the range between 0.80 to 1.15 wpm. The low SR value, 0.80 wpm, made the fancy yarn 1 that had approximately a quarter of its fancy profiles as complete loops.

5.12.1 Conclusions

- To produce good-quality multi-thread bouclé yarns, the Structural Ratio of Multi-thread Fancy Yarn (SR) should be between 0.88 and 1.2 wpm. Smaller values of SR may result in an overfed fancy yarn or irregular bouclé yarn, while higher values of SR may result in a gimp or wavy yarn.
- The higher the value of Structural Ratio of Multi-thread Fancy Yarn the smaller the mean value and variation of the Size of Bouclé Profile.
- The interaction effect of both the number of wraps and the overfeed ratio was that high values of the overfeed ratio increased the Number of Fancy Profiles, while a high number of wraps reduced the Size of Fancy Profile.

5.13 Further Discussions about the Structural Ratio of Multi-thread Fancy Yarn

5.13.1 Importance of the Structural Ratio of Multi-thread Fancy Yarn

The Structural Ratio of Multi-thread Fancy Yarn may form a first step toward finding a relationship between all the structural parameters of multi-thread fancy yarn- including bouclé. Further, its value may define the type of multi-thread fancy yarn. This is because a change in the type of multi-thread fancy yarn may happen when the value the structural ratio changes. Therefore, values of the Structural Ratio of Multi-thread Fancy Yarn should be set in accordance with the various types of multi-thread fancy yarn, in particular loop yarn, bouclé yarn or semi-bouclé yarn, gimp yarn, overfed fancy yarn. For example, it was reported that SR=1.9 ~ 2.5 wpm was suitable to make gimp yarns [24]. Further, the conclusions in Section 5.12.1 recommend that the value of structural ratio of the bouclé yarn should be in the range SR=0.88 ~1.2 wpm.

Furthermore, the Structural Ratio of Multi-thread Fancy Yarn is an indirect measure of the compactness or tightness of the fancy yarn structure. This is because the higher the value of the Structural Ratio of Multi-thread Fancy Yarn, the more compact is the fancy yarn structure. For example, a bouclé yarn has a SR=1.2 wpm is more compact than a bouclé yarn that has a SR=0.90 wpm. Additionally, a change in the compactness of a specific type of fancy yarn may be observed, by changing the value of both the number of wraps and the overfeed ratio together, but keeping the value of the structural ration intact. For example, suppose there are two bouclé yarns that have a structural ratio SR=0.9 wpm. The first of them has η=175% and W=166 wpm, and the second of them has η=200% and W=180%. The second bouclé yarn will be more compact than the first bouclé yarn. So, for a specific type of fancy yarn, i.e. a bouclé yarn, it was possible to manipulate the compactness of its structure, but without changing its structural ratio. However, a noticeable change to the quality, appearance and the Fancy Bulkiness of Fancy Yarn may happen.

In practice, to make a particular type of fancy yarn by applying equation (2.5) of structural ratio, a specific value of overfeed ratio must be selected. This value must be lower than the maximum overfeed ratio recommended for that particular type of fancy yarn. Following this, the job is reduced to calculate the number of wraps that is needed to make the value of the Structural Ratio of Multi-thread Fancy Yarn falls within the acceptable range that is recommended for that type of fancy yarn.

5.13.2 Effects of Unsuitable Values of the Overfeed Ratio and the Number of Wraps on the Structure of Multi-thread Bouclé Yarn

Normally, the effect thread(s) assumes an undulating configuration or corrugations within the final fancy yarn structure because of the overfeed. Those corrugations may be waves, arcs, u-shaped profiles, bouclé profiles, loops, semi-closed or closed knots, etc. Here, it is important to discuss the following two cases:

- If the number of wraps is not sufficiently high, the corrugations may have irregular forms. Some of them may be small; others may be excessively large. Some of them may be short while others elongated. Some of them may be u-shaped; others may have unstable forms.

- However, if the number of wraps is excessively high, the effect thread(s) may become tightly compressed to the core thread over the majority of the fancy yarn sections, while the remaining few sections may have irregular, extra-large fancy profiles. These abnormal, extra-large profiles may easily protrude over the yarn surface and appear as defects.

Consequently, either case is not accepted to happen because it may have negative consequences on the fancy yarn quality. The fancy yarn manufacturer should, therefore, find a number of wraps suitable to the overfeed ratio used. Further, choosing a different, but acceptable, overfeed ratio for the effect thread may require a change to the number of wraps. Eventually, the fancy yarn manufacturer should seek a balance between these two structural parameters.

The solution presented in this thesis for the issue of finding suitable values for the overfeed ratio and the number of wraps was based on using the Design of Experiments. To apply this technique, a wider range of values for those both structural factors was used (as shown in Sections 3.14 and 5.12). Following this, the experimental procedures were conducted and completed through objective and subjective testing. The objective method was based on the quality parameters of fancy yarn (as given in Section 2.3). Moreover, a range of suitable values for the overfeed ratio and another range of suitable values for the number of wraps may be suggested. Those results are particularly useful when the fancy yarns are produced in a spinning mill. In future practice, the situation may become reduced to selecting an overfeed ratio that is suitable to the linear density of the input threads. Following this, it will be necessary to calculate a number of wraps that is required to obtain a value of the Structural Ratio of Fancy Yarn which falls within the practical range.

Since it is possible to manipulate the structure and quality parameters of a specific type of fancy yarn without affecting its structural ratio, it may be preferable to make a fancy yarn with a structure that is not compact. This is achieved by selecting low values for the overfeed ratio and the number of wraps. Such low values of overfeed and wraps may be preferred in industry over higher values for the following reasons:

- A low number of wraps allows for a longer usage of the binder package, which is wound on the hollow-spindle, thus reducing the rate of spindle changes. Consequently, it may increase the productivity of the machine and it may reduce the cost of the time needed to replace the empty hollow spindle.
- It also reduces the tendency of multi-thread fancy yarns to snarl on themselves, thus improving the quality of such fancy yarns. Additionally, since snarled yarns are usually dealt with by steaming before further processing, for example in knitting or weaving, while there is no need to steam straight, regular fancy yarns, the result is reductions in the time of processing, preparation time and costs.
- Further, a lower number of wraps may make the handle of fancy yarns softer. This means improving its quality.
- Moreover, since a low overfeed ratio allows for a reduction in the usage of raw material, it reduces the costs of the usually expensive effect materials; thus, it may increase profits.

5.14 The Effect of Tensioning of the Core Thread on Structure and Quality of Multi-thread Fancy Yarn

5.14.1 Observations about the Configuration of the Core Thread within the First Spinning Zone

The configuration of the core thread in the First Spinning Zone was important to this study. With regard to fancy yarn 1, it was observed that all the fancy yarn components, including the core thread and the binder, had helical configuration. The helix of the core resulted because the core thread entered this zone in a slack motion. This slack motion allowed the core thread to balloon. Furthermore, the core thread was under the effect of pressure from the binder and, as a result, it was bending easily. The core thread of fancy yarn 2 had also a spiral configuration which was similar to that of the binder and the effect thread (in its spiral sections). However, the core threads of yarns 3, 4 and 5 were straight due to the high levels of Tension.

5.14.2 Numerical Results

The numerical results of the testing procedures are given in Table 43.

Table 43: Results of the Testing Procedures to Identify the Impact of the Core Tension on the Bouclé Yarn Structure

Fancy Yarns	Tension of the Core Thread, g	Size of Fancy Profile mm^2	SD of Size mm^2	Circularity Ratio	SD of Circularity	Number of Fancy Profiles m^{-1}	SD of Number m^{-1}	ShF $mm^2\ m^{-1}$
Yarn 1	0	19.47	7.95	0.64	0.12	36.70	2.75	714.45
Yarn 2	5	17.69	6.17	0.47	0.13	35.50	3.98	627.98
Yarn 3	8	24.46	11.23	0.48	0.19	25.20	4.34	616.47
Yarn 4	17	22.27	6.24	0.49	0.15	26.60	3.27	592.38
Yarn 5	21	44.26	30.52	0.35	0.23	22.20	2.90	982.61

This table shows that the fancy yarns of this experiment were different in terms of the Number of Fancy Profiles, the Size of Fancy Profile and the Circularity Ratio of Fancy Profile. Those differences were analysed statistically against the Tension using the One-way ANOVA testing. It was found for all these statistical testes that the p-value= 0.000. This meant that the probability of obtaining those differences by chance was approximately zero. Therefore, those differences were real and were further analysed as follow:

With regard to the Size of Fancy Profile, Figure 56 shows that the low levels of tension created small fancy profiles, i.e. when the Tension of the core thread was set at no more than 5 g (for the fancy yarns 1 and 2). By increasing the Tension, the fancy yarns started to develop larger fancy profiles. When the Tension was increased from approximately zero (for yarn 1) to 17 g (for yarn 4), the increase in the area of the profiles was less than 3 mm^2. When the Tension was increased from 17 to 21 g, however, the average area of the profiles was doubled from about 22 mm^2 to about 44 mm^2.

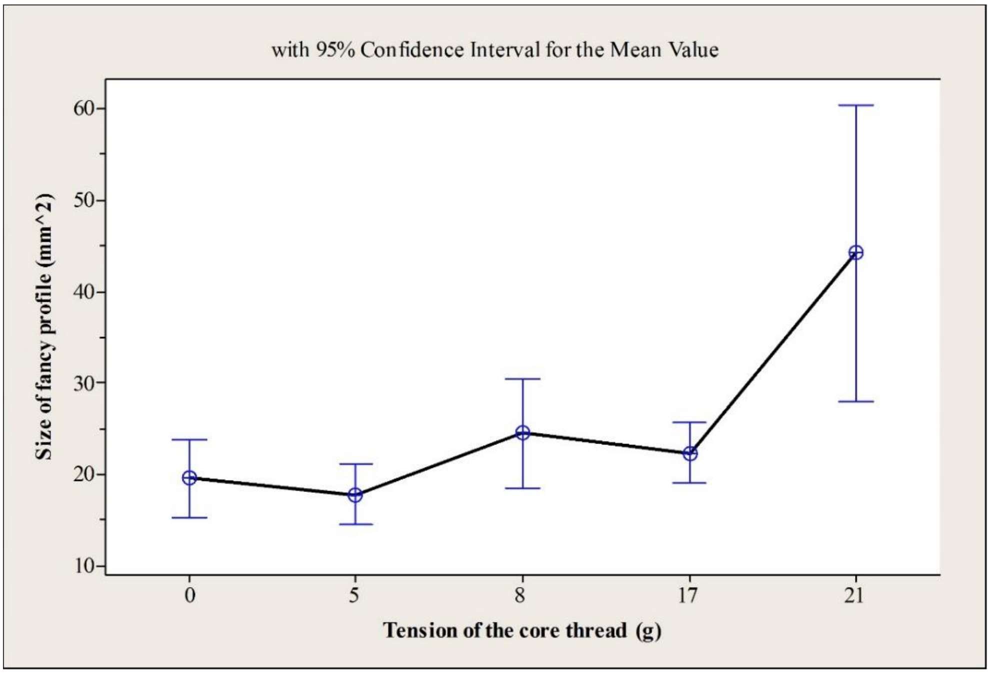


Figure 56: Relationship between the Size of Fancy Profile and Tension of the Core Thread

There was also an increase in the variability of the Size of Fancy Profile for the highest value of Tension as shown in the same figure and in Table 43. Since the quality of the fancy yarns deteriorated dramatically beyond the value 17 g of Tension, it was thought that this level of Tension was critical for the manufacturing process when considering the materials and the machine settings used. However, when the Tension was increased from approximately zero to 21 g, the Number of Fancy Profiles decreased by 40% from 36.7 to 22.2 per meter (as shown in Figure 57). The relationship between the Number of Fancy Profiles and the Tension was linear and the regression equation was:

$$Number\ of\ Fancy\ Profiles = 35.9 - 0.648 \times Tension\ of\ the\ core\ thread \qquad (5.17)$$

where the fancy profiles were counted per metre and Tension was measured in gram.

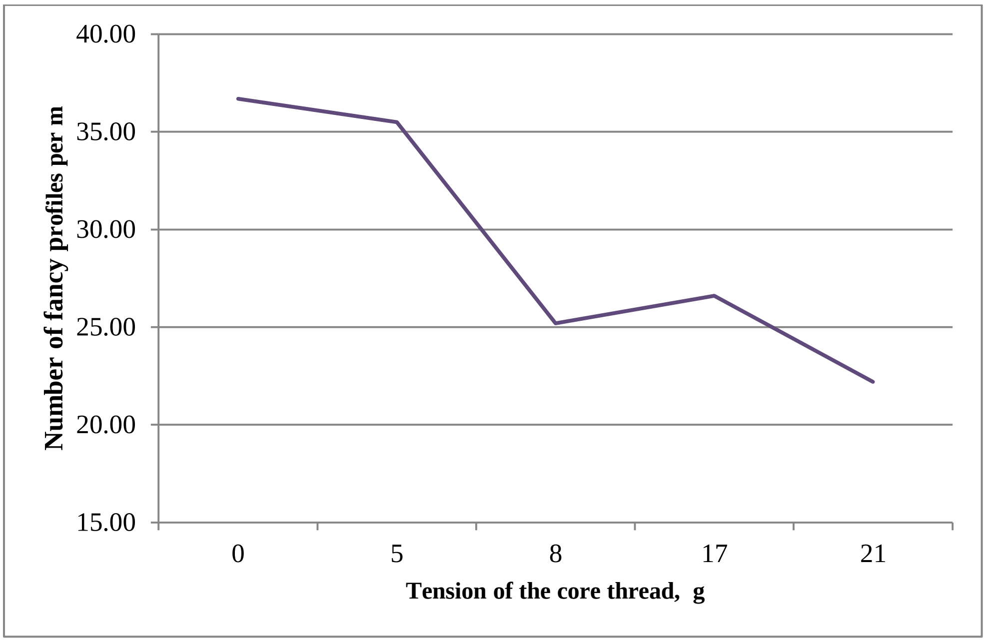


Figure 57: Relationship between the Number of Fancy Profile and Tension of the Core Thread

The statistical study of this regression model shows that it was significant at a confidence level 90 % and the p-value of the ANOVA testing was 0.058 (i.e. significant at significance level α 0.10). Further, the results of the t-test indicated that the core Tension was a significant factor at any significance level $\alpha>0.058$, e.g. 0.06 or 0.10. Moreover, the values of the Coefficient of Determination was R^2=74.9% which indicated that 74.9% of the variation in the Number of Fancy Profiles (i.e. the dependent variable) was explained by the variation in the core thread Tension (i.e. the independent variable). Further, the Standard Error was SE=3.74 profile per meter, which was a small value. Therefore, the Tension was also a key factor in explaining the variability of the Number of Fancy Profiles and the model given in equation (5.17) can be used to predict the Number of Fancy Profiles based on the value of Tension of the core thread.

With regard to the Circularity Ratio of Fancy Profile, Figure 58 demonstrates that the circularity ratio decreased from approximately 64% to only 35% with the increase of Tension of the core thread from approximately 0 to 21g. Therefore, the Tension had an impact on the Circularity Ratio of Fancy Profile. Furthermore, depending on the objective approach and the recommendations and definitions published previously [4, 28], the fancy profiles of yarn 1 were bouclé, while those of yarn 4 may be regarded as semi-bouclé. However, those of yarn 5 were not bouclé.

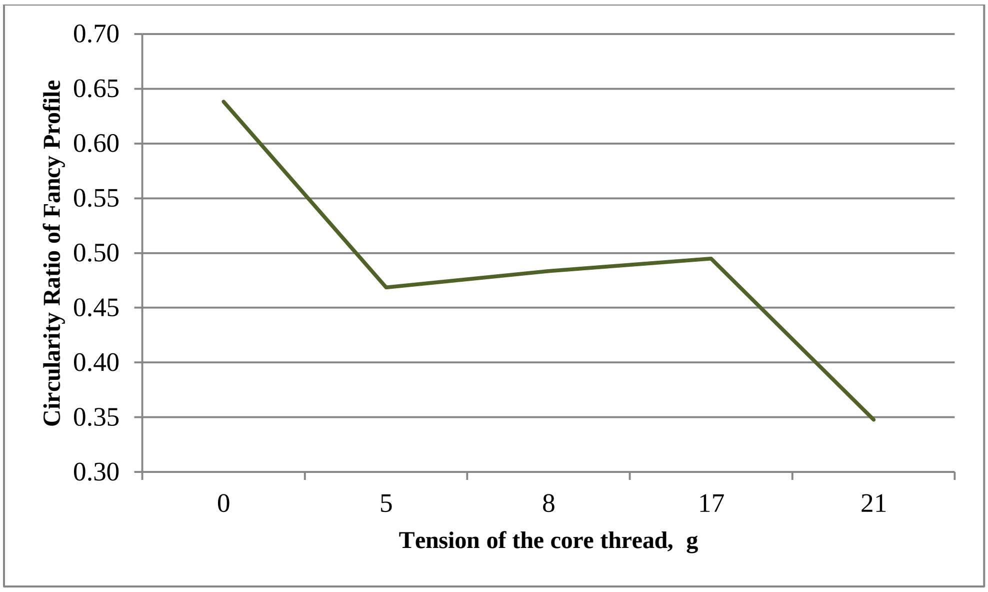


Figure 58: Relationship between the Circularity Ratio of Fancy Profile and Tension of the Core Thread

To understand the impact of the core thread Tension on the Absolute Fancy Bulkiness of the Fancy Profiles, Table 43 and Figure 59 were instructive. However, it is firstly important to note that the high value of the Shape Factor of Fancy Yarn (ShF) for yarn 5, which was made at the highest value of Tension equalling 21g, did not reflect the visual Absolute Fancy Bulkiness of the Fancy Profiles. It rather resulted from defective and extremely large fancy profiles as indicated in the subjective assessment (below). Therefore, the value of the Shape Factor of Fancy Yarn of yarn 5 was discarded in the analysis. By ignoring this value, Figure 59 shows that the Shape Factor of Fancy Yarn decreased when the Tension increased while making the fancy yarns.

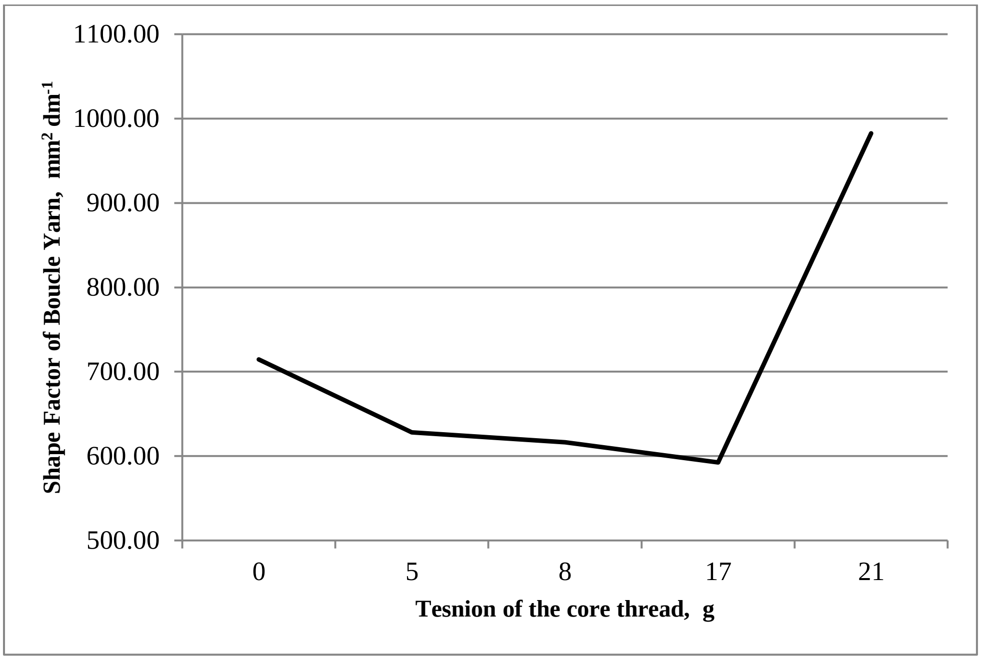


Figure 59: Relationship between the Shape Factor of Fancy Yarn and Tension of the Core Thread

5.14.3 Subjective Assessment

The subjective assessment of the fancy yarns made for of this experiment can be matched with the images of the five fancy yarns as provided in Figure 60. This figure clearly illustrates that those fancy yarns were different from each other in appearance and morphology. Fancy yarn 1 appeared to have regular structure compared to the rest. Further, the fancy profiles of this yarn were relatively evenly distributed over its surface and they were separated with wide sigmoidal or spiral sections. Furthermore, the fancy profiles were normal bouclé profiles. However, a minority of the bouclé profiles were forced to locate spirally sideways over a turn or a half-turn of the binder wraps. In summary, fancy yarn 1 was a multi-thread bouclé yarn.

Fancy yarn 2 also demonstrates regular structure by having relatively regularly distributed fancy profiles. Some fancy profiles were circular, arcs or waves. Further, some of the fancy profiles were closed; others were located sideways over the yarn surface, because they were forced to spiral by one or a half-turn of wraps. The sigmoid and spiral sections were fewer in comparison to the bouclé sections or corrugations of the same fancy yarn. Furthermore, the number of the profiles on both the fancy yarns 1 and 2 appeared to be similar. Therefore, fancy yarn 2 was also a multi-thread bouclé yarn.

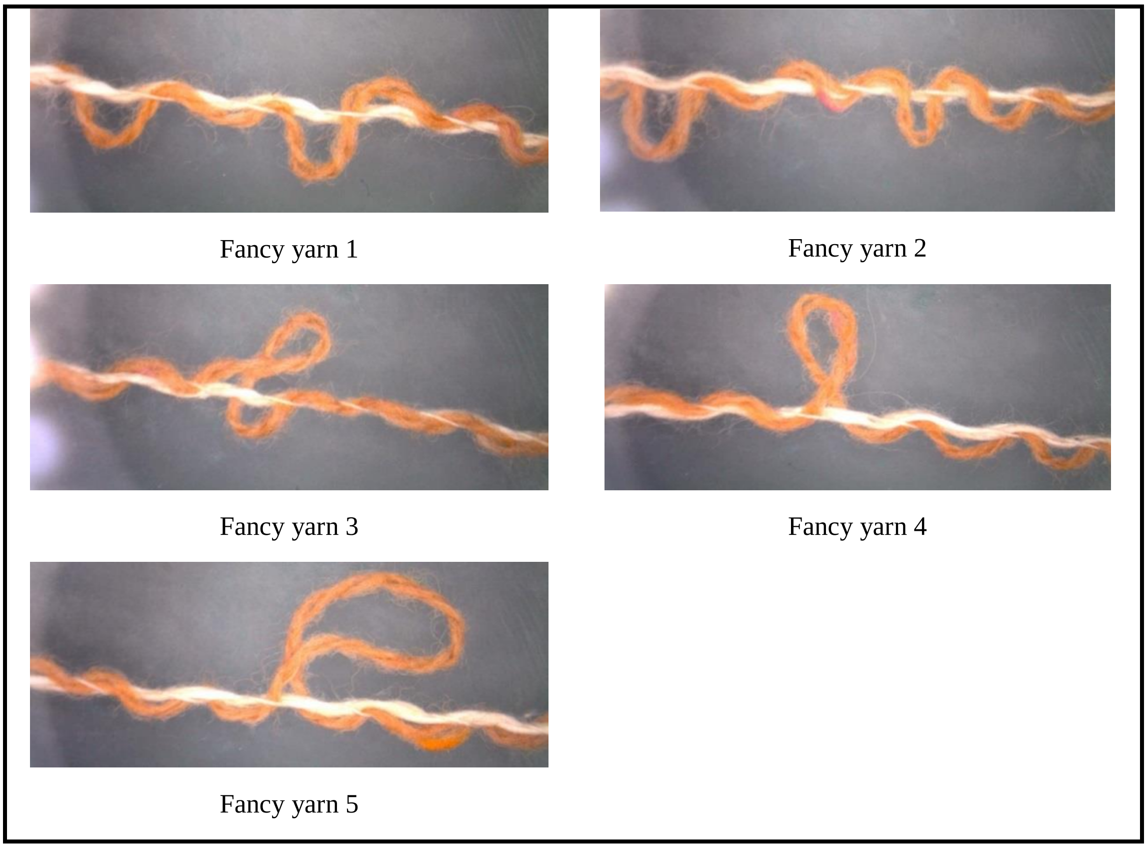


Figure 60: Images of the Fancy Yarns Made to Test the Impact of Tension of the Core Thread on the Bouclé Yarn Structure

Regarding fancy yarn 3, the mean value and standard deviation of the Size of Fancy Profile was higher, comparing to fancy yarns 1 and 2. Besides bouclé profiles, fancy yarn 3 had other types of fancy profile such as corrugations; waves; diagonal bouclé profiles (as a result of unequal length of legs of the fancy profile); closed, elongated fancy profiles; and some circular profiles. Further, the sections between the fancy profiles were narrow spirals. The uniformity of distribution of the fancy profiles between the spiral sections was also low compared to the fancy profiles of yarns 1 and

2. This happened due to the higher variation in the area of profiles for yarn 3. The increased area of fancy profiles for the fancy yarn 3 resulted in a dramatic reduction in the number of the fancy profiles compared to fancy yarns 1 and 2. No specific commercial name of fancy yarn was capable of describing fancy yarn 3. However, it was possible to regard it as a multi-thread overfed fancy yarn.

Regarding yarn 4, the number of fancy profiles appeared to be similar to that of yarn 3, i.e. lower than that of yarns 1 and 2. Further, the fancy profiles were a combination of bouclé, loops, diagonal bouclé, elongated closed profiles, arcs, etc. All of which were separated by the spiral and sigmoidal sections. Moreover, some fancy profiles were clustered in pairs at the same location along the axis of yarn 4. It was only possible to describe this yarn as a multi-thread overfed fancy yarn.

Finally, yarn 5 had spiral sections separated by elongated fancy profiles. The majority of those fancy profiles were much larger than those of the other four fancy yarns. However, the remaining fancy profiles were small. As a result, the variability of the area of the fancy profile was rather high. Additionally, some of the extremely large, closed fancy profiles were projecting crosswise; the others were either flexed, collapsed, laid over the yarn surface or rolled around the yarn surface. Furthermore, the distribution of the fancy profiles along the yarn axis was highly irregular. Due to the extremely large fancy profiles, the usage of the Shape Factor of Fancy Yarn to describe the Absolute Fancy Bulkiness of this fancy yarn was inappropriate. In conclusion, it was recommended not to make such a fancy yarn for commercial applications.

5.14.4 Discussion

The impact of Tension of the core thread, during the manufacture of a multi-thread fancy (or bouclé) yarn, on a hollow-spindle spinning machine, was understood by considering the configuration of the core thread in the First Spinning Zone. Generally speaking, because of the overfeed ratio and due to the false-twist hook that is attached to the out-let mouth of the spindle, the effect thread assumes a helical path around the core thread. Further, a sufficiently tensioned core thread becomes the straight axis of the helix. If the effect-thread helices become wider than needed, the resultant fancy profiles may become extremely large. Additionally, a few large fancy profiles per unit length may result. So, the sigmoidal sections may become extremely narrow. In other words, the quality of the final yarn may become poor, which may render the fancy yarn losing its required fancy appearance. However, if the core thread is left to rotate free of tension, when it enters the First Spinning Zone, the rotating core thread will form a balloon in the First Spinning Zone; in some special cases, two balloons might be formed. Therefore, the situation may become different and the quality of the resulting fancy yarn may improve.

When the core thread balloons in the First Spinning Zone, it becomes closer to the effect-thread helices in each of the successive segments of the effect thread. So, when the spiralling binder fixes the core thread and the effect thread together the chance of forming extra, and small, fancy profiles increases. Moreover, the chance of forming arcs, waves, corrugations, or spiral sections on the fancy yarns increases. Furthermore, the height of the fancy profile becomes smaller. Consequently, the ultimate fancy yarn will have smaller fancy profiles of similar sizes, more fancy profiles and more waves and arcs, compared with the case of a tensioned, straight core thread. This means that the structure and quality of the fancy yarn may improve without changing the number of wraps or the overfeed ratio. In some special cases, it is possible to make a fancy bouclé yarn even by using a relatively low overfeed ratio, e.g. fancy yarns 1 and 2.

Controlling the level of Tension of the core thread was possible via the tensioning rollers as shown in Figure 14. Usually, the core thread is nipped by the rotating tensioning rollers which control its movement. A slightly extra rotational speed of those rollers than the delivery rollers suffices to push the core thread forward, to the First Spinning Zone, free of Tension. The minimum level of Tension of the core thread may be considered as the Tension that is needed to allow the core thread to balloon.

By discarding yarn 5 for the reasons stated in the previous section, the advantages of fancy yarn 1 over the other yarns were as follows: fancy yarn 1 had the highest Number of Fancy (Bouclé) Profiles which were larger than those of fancy yarn 2. Further, the Size of Fancy (Bouclé) Profile of yarn 1 was 19.47 mm^2, which was suitable to the yarn thickness. Additionally, fancy yarn 1 had the highest value of Shape Factor of Fancy

Yarn, i.e. 714.45 mm^2 m^{-1}. This value made yarn 1 the fancy yarn which had the highest Absolute Fancy Bulkiness. Moreover, yarn 1 had the highest value of Circularity Ratio, i.e. 64%. As a result, fancy yarn 1 was regarded as the best-quality fancy bouclé yarn. The second bouclé yarn also had good quality, but with lower values of Shape Factor of Fancy Yarn (624.98 mm^2 m^{-1}) and the Circularity Ratio of Fancy Profile (47%) than the first bouclé yarn. The quality of the fancy yarns deteriorated severely when yarn 5 was made using the highest level of Tension.

5.14.5 Conclusions

Low level of Tension of the core thread, while manufacturing multi-thread fancy yarns (on hollow-spindle spinning machines and other hollow-spindle fancy twisters):

- gave rise to the Number of Bouclé Profiles along the length of the ultimate bouclé yarn;
- resulted in relatively smaller bouclé profiles and reduced the variability of the Size of Bouclé Profiles;
- increased the Circularity Ratio of Bouclé Profile and the Shape Factor of Bouclé Yarn;
- promoted regular spiral and sigmoidal sections and wavy corrugations between the fancy profiles; and
- By reducing the Tension of the core to its minimum level it was possible to manufacture bouclé yarns using only 50% real overfeed ratio of one effect thread rather than two effect threads.

Therefore, low Tension of the core thread:

- was beneficial to the structure and quality of bouclé yarns since it regulated the style of such a fancy yarn; and
- helpful to reduce the cost of production, based on minimising the usage of the input material, in particular the relatively expensive effect thread.

5.15 Influence of Width of Base of the Spinning Triangle on the Structure of Multi-thread Bouclé Yarn

The experimental procedure, material and the machine settings for this experiment are given in Section 3.16 and the yarns made for this experiment are shown in Figure 61.

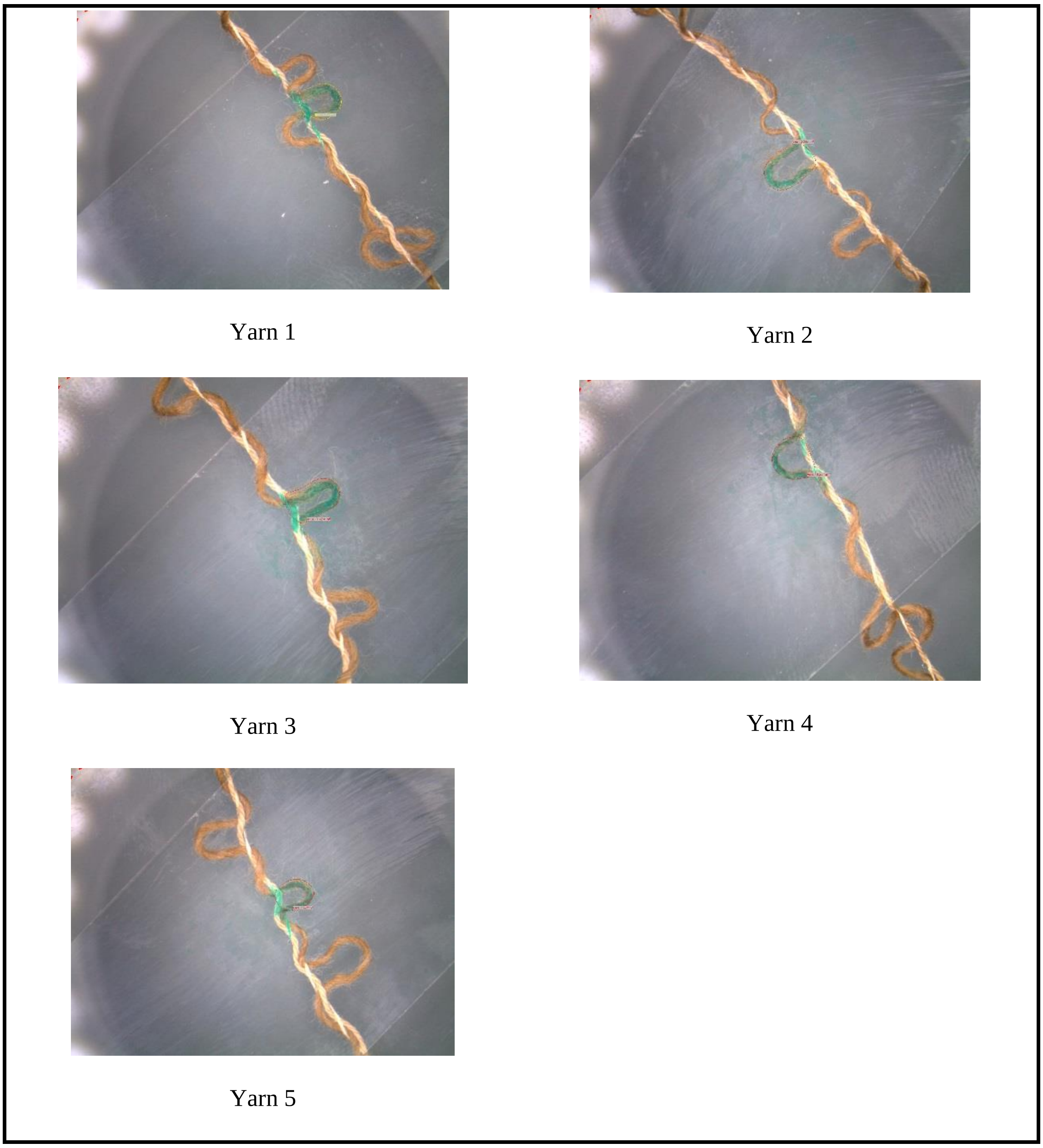


Figure 61: Images of the Boucle Yarns Made to Test the Impact of Spinning Triangle on Structure of Bouclé Yarn

The images of this figure indicate that the yarns made were similar in structure because all of them had bouclé profiles and regular sigmoidal sections. Those yarns were tested objectively and the results of the testing procedures are given in Table 44. The data of this table indicate that the spinning triangle had no effect on the structure of multi-thread bouclé yarns and similar overfed fancy yarns such as gimp fancy yarns or wavy fancy yarns.

Table 44: Results of Assessing the Impact of Width of the Spinning Triangle on the Bouclé Yarn Structure

Bouclé Yarn	Range of Width of Spinning Triangle (mm)	Size of Bouclé Profile (mm^2)	SD of the Size (mm^2)	Number of Bouclé Profiles (per dm)	SD of the Profile Number (per dm)	Circularity of Bouclé Profile (%)	SD of the Circularity Ratio (%)
Yarn 1	4 - 5	13.39	3.80	7.3	0.90	57	17
Yarn 2	7 - 8	14.65	4.19	7.2	1.20	53	17
Yarn 3	9.5 - 10.5	12.85	6.72	7.8	1.60	55	20
Yarn 4	12.5-13.5	13.59	4.15	7.3	0.90	56	18
Yarn 5	15.5 - 16.5	14.40	6.59	6.5	1.40	56	18

This result may have happened because the width of the spinning-triangle did not affect the First Spinning Zone. Therefore, given the settings used for the machine, it is concluded that the distance between the core thread and the effect thread at the beginning of the First Spinning Zone had no influence on the structure of bouclé yarns.

5.16 Assessment of the Variability of the Hollow-spindle Spinning Machine

The yarns made for this experiment are shown in Figure 62. The images shown in this figure indicates that all the bouclé yarns had variability in the structure because the bouclé profiles and the semi-bouclé profiles were not consistent in size. However, it was difficult to define the yarns which had high variability and those which had lower variability. So, the objective testing was required to conduct.

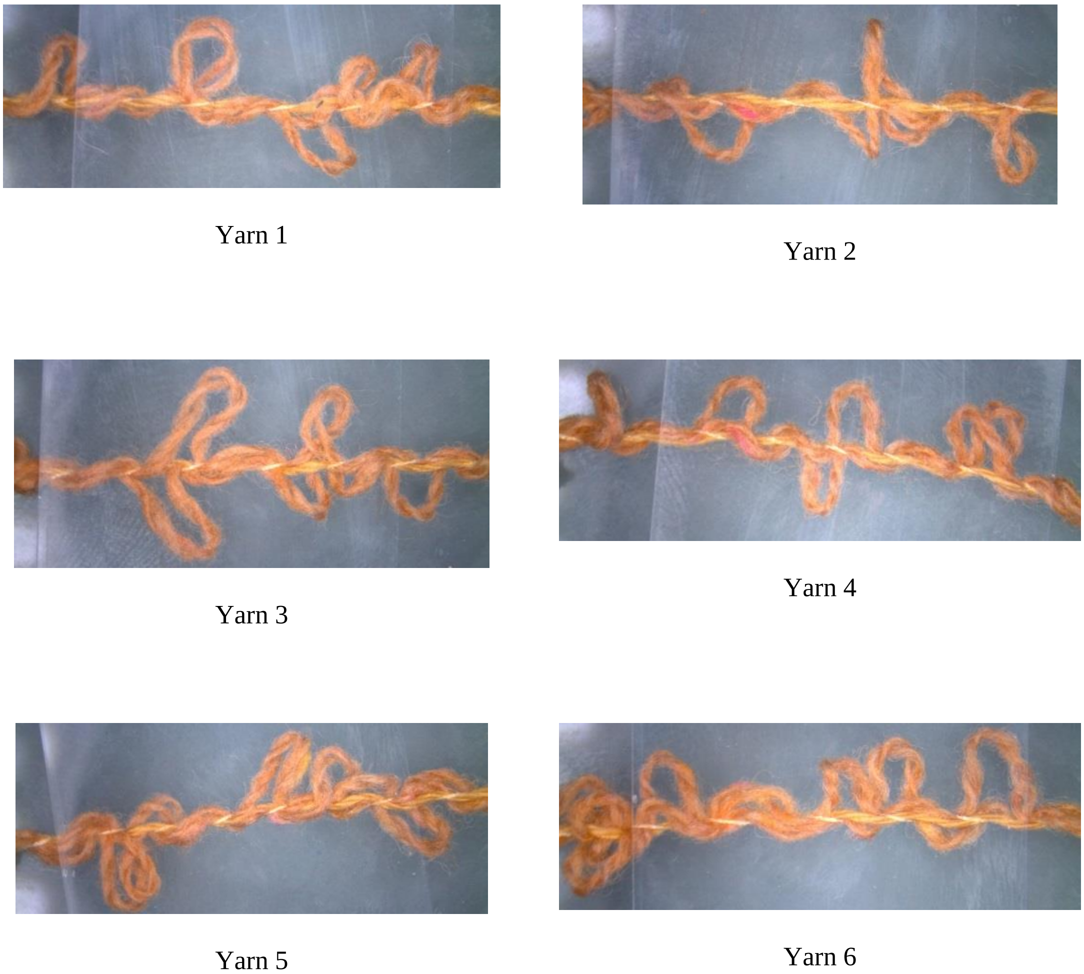


Figure 62: Images of the Yarns Made to Estimate the Variability of the Machine

5.16.1 Numerical Results

The data collected are given in Table 45. This table shows that there were differences between the fancy yarns made in terms of the mean value and the standard deviation of the Size of Fancy (Bouclé) Profile, Number of Fancy (Bouclé) Profiles and the Shape Factor of Fancy (Bouclé) Yarn.

Table 45: Results of Assessment of the Influence of the Variability of the Gemmill & Dunsmore #3 Hollow-spindle Machine on the Bouclé Yarn Structure

Bouclé Yarn	Time from Start-up of the Machine, min	Size of Bouclé Profile, mm^2	SD of Size, mm^2	Number of Bouclé Profiles, dm^{-1}	SD of Number, dm^{-1}	ShF of Bouclé Yarn, $mm^2\ dm^{-1}$
yarn 1	0	18.41	6.79	14.67	1.70	270.03
yarn 2	30	19.28	5.00	15.20	2.50	293.02
yarn 3	60	18.69	5.35	15.50	2.30	289.62
yarn 4	90	17.25	3.72	14.07	3.39	242.65
yarn 5	185	18.41	4.28	15.07	2.46	277.44
yarn 6	205	20.74	6.33	16.33	2.16	338.69

The results related to the Size of Bouclé Profile are presented in Figure 63.

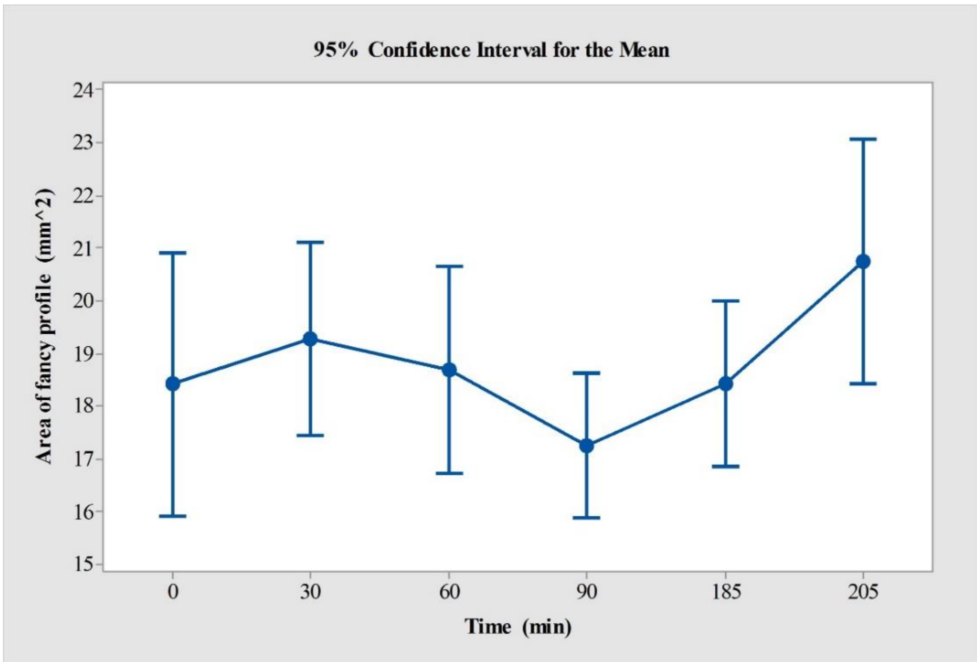


Figure 63: Variation in the Size of Bouclé Profile Caused by the Machine over Time

This figure indicates that there was a remarkable variation in the area of the profiles over time. However, the confidence intervals of this bouclé yarn property were all intervening. Therefore, only the yarns which had high deviation from the average of all yarns were compared with each other, i.e. the peaks corresponding to yarn 2, yarn 4 and yarn 6. The results of the t-test confirmed that the bouclé profiles of yarn 2 were statistically larger than those of yarn 4 because the p-value was $0.037 < \alpha=0.05$. Additionally, the bouclé profiles of yarn 6 were statistically larger than those of yarn 4 because p-value= $0.005 < \alpha=0.05$. However, no significant difference was found between yarn 2 and yarn 6 because the p-value = 0.158 of the t-test.

Since yarns can be different in the variation as well as the mean values of any property, Levene's Test was conducted to test if all variances of the Size of Bouclé Profile for the yarns were equal. Figure 64 gives the results of this test. The p-value was 0.126 which indicates that there was no single variance that was different from the other variances taken as a whole. However, Figure 64 also shows that the Confidence Interval (CI) of the variance of yarn 4 (i.e. made at minute 90) was marginally intervening with that of yarn 6 (i.e. made at minute 205). Repeating Levene's Test for only yarn 4 and yarn 6 resulted in a p-value =0.018 < α=0.05 which indicates that the variances of these two yarns were different. This means that yarns 4 and 6 were different in terms of the variation in the Size of Bouclé Profile.

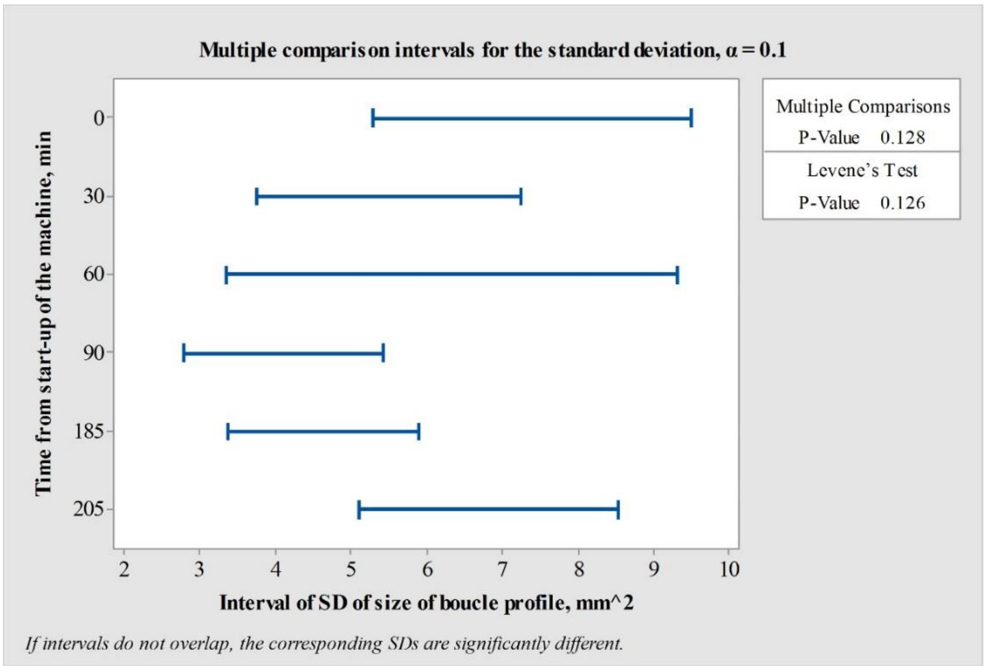


Figure 64: Results of Testing the Variances in the Size of Boucle Profile

In terms of the consistency of the Size of Bouclé Profile, the CV% values of the area of the bouclé profiles changed remarkably over time as shown in Figure 65.

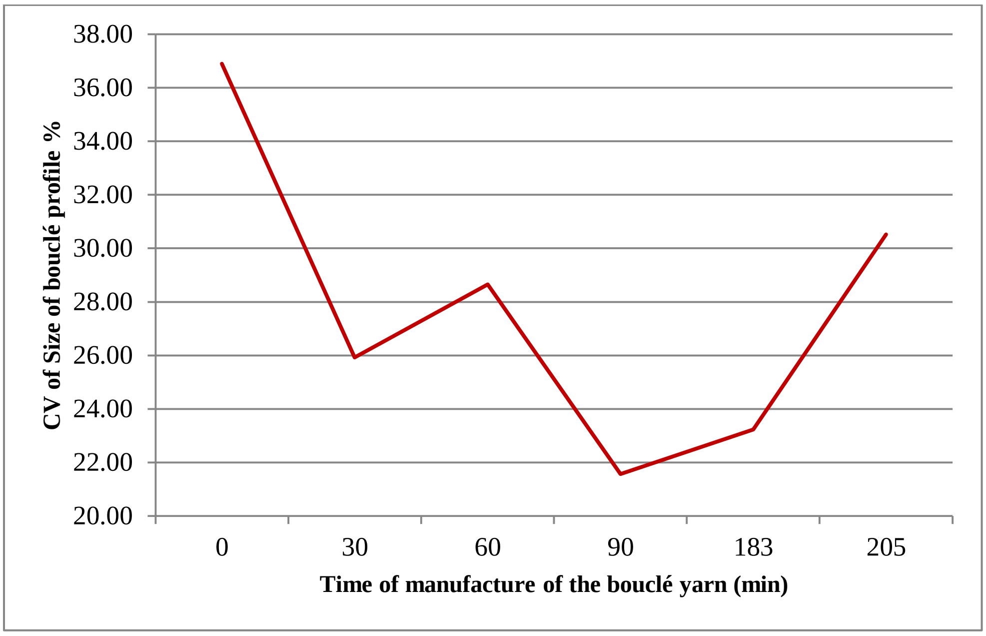


Figure 65: Variability of the Size of Bouclé Profile over Time

In terms of the Number of Bouclé Profiles, Levene's Test was also conducted and the results are shown in Figure 66.

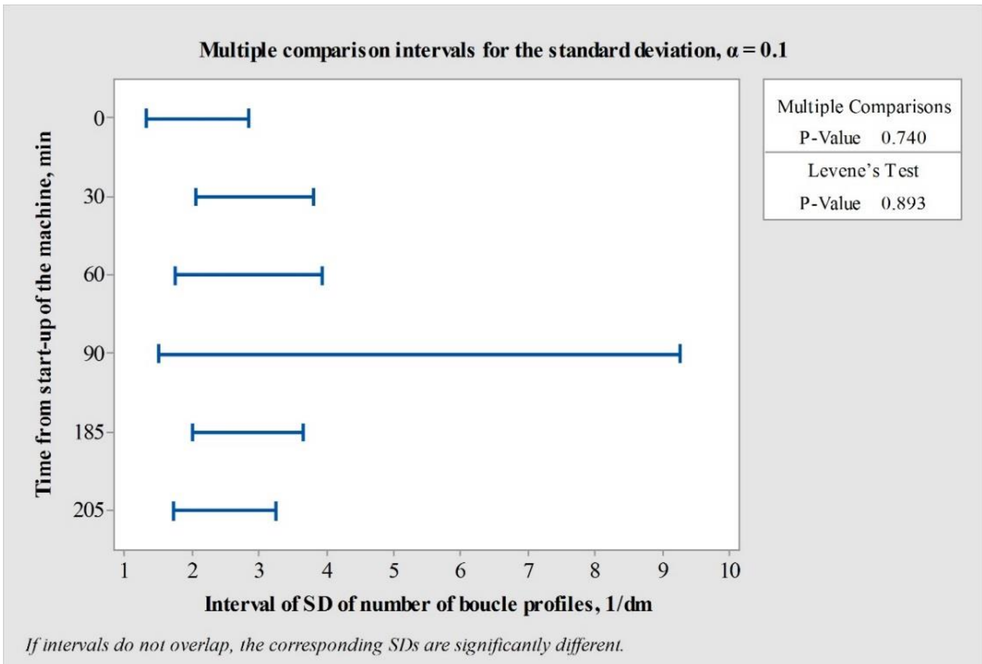


Figure 66: Results of Testing the Variances of the Number of Boucle Profiles

This test did not indicate any statistical difference amongst the bouclé yarns. However, this figure indicates that the variance of yarn 4 was extremely higher than the variances of the other bouclé yarns. Therefore, a paired comparison of yarn 4 with one of the others, e.g. yarn 1, using Levene's Test was conducted. This test confirmed that the number of bouclé profiles of these two yarns were different and the p-value was $0.043 < \alpha=0.05$. This also meant that the variance of yarn 4 was also statistically different from the remaining fancy yarns.

In terms of the Circularity Ratio of Fancy (Bouclé) Profile, Table 45 indicates that only the bouclé profiles of yarn 2 appeared to be slightly more circular than the other fancy yarns.

With regard to the Shape Factor of Fancy (Bouclé) Profile, Table 45 indicates that the ShF changed from yarn to yarn over time. However, the CV% of the ShF was 11.13 %. This level of variation was acceptable for fancy yarns because their structure is already based on a minimum level of variability.

5.16.2 Discussion

Normally the variability of a product is attributed to three main sources [69]: variability of raw materials, variability caused by workers in the shop floor and/or variability caused by the manufacturing process itself. The process variability may result from unstable levels of the factors and from random variation. So, the same experiment could give slightly different results of the same product properties from a trial to trial [19]. Based on this, it is possible to control the variability of the product characteristics by controlling the variability at the source. Careful sourcing of raw material and hiring a skilful workforce may usually minimise the first and second sources of variation. Further, by controlling the process, it is possible to reduce the level of variability of manufactured products. Quality Control of manufacturing processes is the approach to solve the third source of variation.

In this experiment, it was not possible to obtain raw materials with low variability. The CV% of the bending stiffness of the effect thread (B_e) was approximately 38.34 %. This high CV% value may have resulted from several reasons (as mentioned in Section 5.7.1). The most important one is the variation in the linear density as the linear density is written as a squared term in the bending stiffness equation [23]. Furthermore, the variability of the bending stiffness has two forms:

- local or short-term variation (resulting from short-term yarn imperfections), and
- extending or long-term variation (resulting from long-term yarn imperfections).

Based on the experimental work given in Sections 5.7.1 and 5.7.11, the CV% of the bending stiffness was observed to be related to a high extend to the short-term variations of the threads. The impact of variation in bending stiffness affected the bouclé yarn structure. This is because the bending stiffness affects the way and extend in which the effect thread flexes in order to form the bouclé profile or the sigmoidal sections, so it has a profound impact on the ultimate fancy yarn structure (Section 5.8.6).

Since the machine was operated by the same person, it was not expected to assign any noticeable variation to the workforce. Instead, it would be more appropriate to assign parts of the variation to random variation in the process and the unstable levels of the factors. The last reason was understood as follows: since the operating parts of the machine are driven through gears and transmitting belts, so when running the machine, the temperature of the belts increases because of friction. Subsequently, the belts may extend slightly which reduces or eases the grip of the belts on the operating parts. This may cause changes in the rotations of the operating parts, in particular supply rollers, delivery rollers and the hollow-spindle. Eventually, when time elapses, the various speeds of the machine are expected to drift or change marginally, which may affect the manufacturing process of the fancy yarns and their structure.

5.16.3 Conclusions

Over a period time of running the G&D hollow-spindle spinning machine, deviations started to appear within the bouclé yarn characteristics. Mainly, the Size of Bouclé

Profiles was negatively affected. However, those deviations were acceptable when measured using the Shape Factor of Bouclé Yarns (ShF). The variability of the ShF did not exceed 12 %.

5.17 Mapping the Interaction Patterns of Bending Stiffness of Both the Core Thread and the Effect Threads

5.17.1 Initial Results

The results of the testing procedures of the bouclé yarns which were made for each trial are given in Table 46. The term C1&E1 refers to the bouclé yarn which was made by using the first level of the core thread, C1, and the first level of the effect thread, E1; and so forth for other symbols.

Table 46: Summary of the Results of the Interaction between the Bending Stiffness of the Core Thread and that of the Effect Threads

Standard-Order Trial Number	Yarn Designation	Size of Bouclé Profile (mm^2)	SD of Size of Bouclé Profile (mm^2)	Number of Bouclé Profiles (dm^{-1})	SD of Number of Profiles (dm^{-1})	ShF of the Yarn ($mm^2\ dm^{-1}$)
1	C1&E1	10.29	2.55	20.0	3.4	206
2	C1&E2	11.93	3.09	12.7	2.6	152
3	C1&E3	14.98	4.66	9.6	2.3	144
4	C2&E1	9.83	2.67	16.6	3.9	163
5	C2&E2	10.59	3.28	15.2	2.1	161
6	C2&E3	14.15	4.54	9.9	3.1	140
7	C3&E1	12.03	3.60	20.0	4.8	241
8	C3&E2	10.24	3.06	16.9	2.4	173
9	C3&E3	13.15	3.13	11.8	3.0	155

The data of this table, as they resulted, were raw and they were not useful in their current form. Therefore, they were analysed using *response tables* and Minitab to obtain more useful results as given in Section 3.19.

5.17.2 Influence of Factors on Size of Bouclé Profile

The analysis explained in Table 17 indicates that the bending stiffness of the core thread had little influence on the Size of Bouclé Profile. However, Figure 67 indicates that the higher the bending stiffness of the effect thread, the larger the bouclé profile. This is because the relatively stiff effect threads were difficult to bend while making the bouclé yarns. Therefore, they needed longer time to bend and they formed larger helices in the First Spinning Zone. The result of this was obtaining larger bouclé profiles. In order to avoid such an output, it was suffice to use more flexible effect threads. The binder, therefore, was able to force the effect-thread helices to bend into the structure of the intermediate product within the hollow spindle.

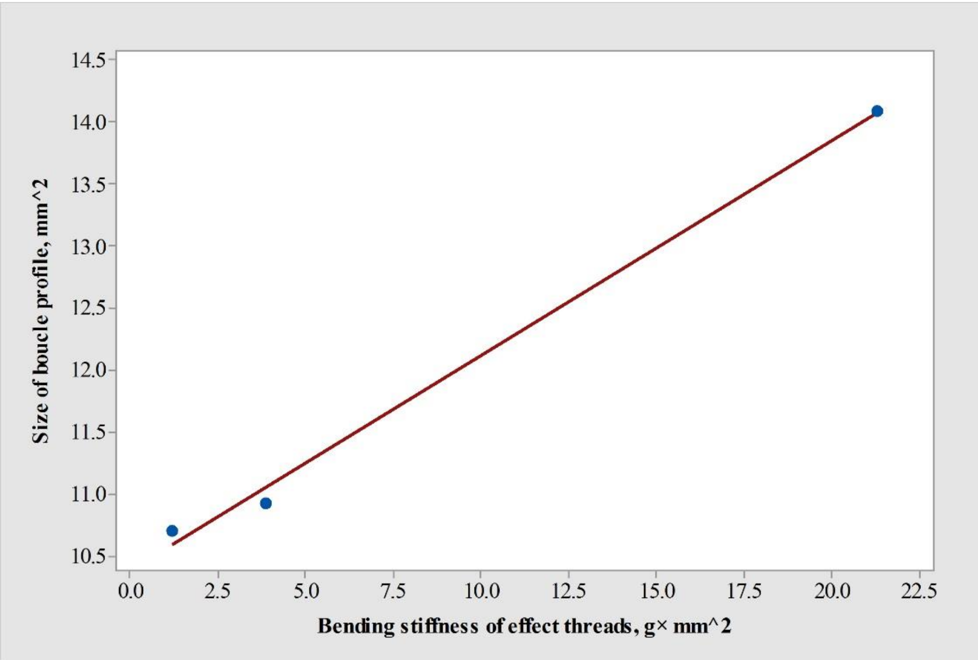


Figure 67: Plot of Main Effect of the Bending Stiffness of the Effect Threads on the Size of Bouclé Profile

The relationship of Figure 67 represented a regression model, even by considering the bending stiffness of the core thread, B_c, as follows:

$$Size\ of\ Bouclé\ Profile = 10.5 - 0.0136\,B_c + 0.173\,B_e \qquad (5.18)$$

Where: the Size of Bouclé Profile is measured in mm^2 while B_c and B_e are measured in g mm^2. This relationship was significant at a confidence level 99%, and the p-value of the ANOVA testing was 0.01.

The plot of interaction between the bending stiffness of the core thread and the bending stiffness of the effect threads related to the Size of Fancy (Bouclé) Profile is given Figure 68. Generally speaking, since there were semi-parallel lines in this figure, it did not indicate strong interactions between those two factors. An interaction only happened when using the most flexible effect threads (denoted by blue line) with the stiffest core thread (i.e. when making bouclé yarn E1&C3). This combination increased the area of the profiles by approximately 2 mm^2 in comparison with the interactions E1&C1 and E1&C2.

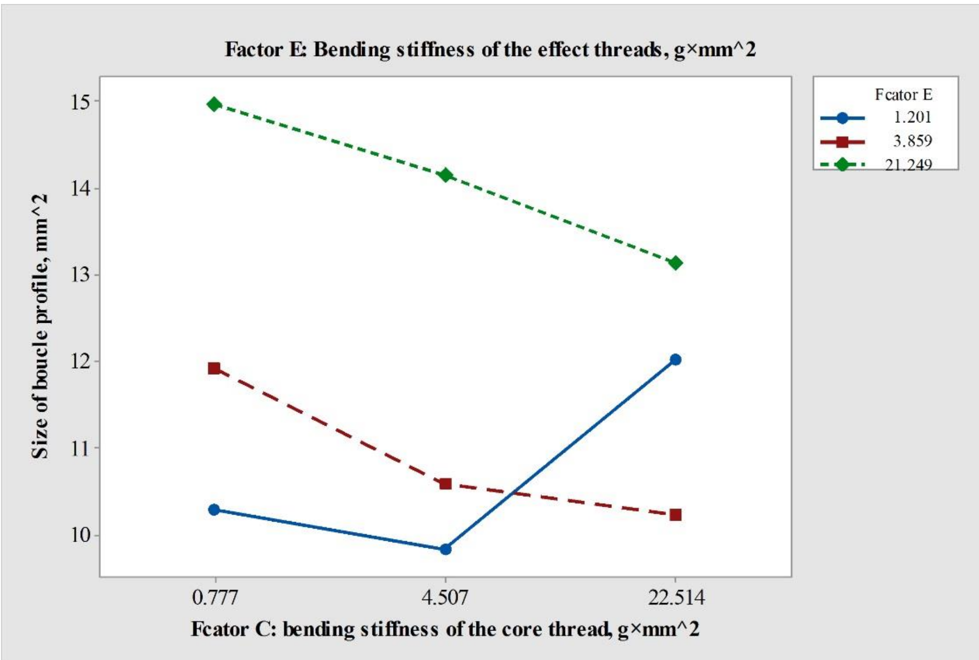


Figure 68: Plot of the Interaction Effect of Factors E and C on the Size of Bouclé Profile

5.17.3 Influence of Variability of Factors on Variation in the Size of Bouclé Profile

The core component had little impact on the variability of the Size of Bouclé Profiles. However, Figure 69 indicated that the higher the variation in bending stiffness of the effect threads (B_e), the higher the variability of the Size of Bouclé Profile. The CV% of the production process[23] regarding the Size of Bouclé Profile was 28.5 %. Although this value was high, it may be preferred aesthetically by fancy yarn designers. In all case, the variation in the stiffness of the threads may be the main source of variation in the area of profiles.

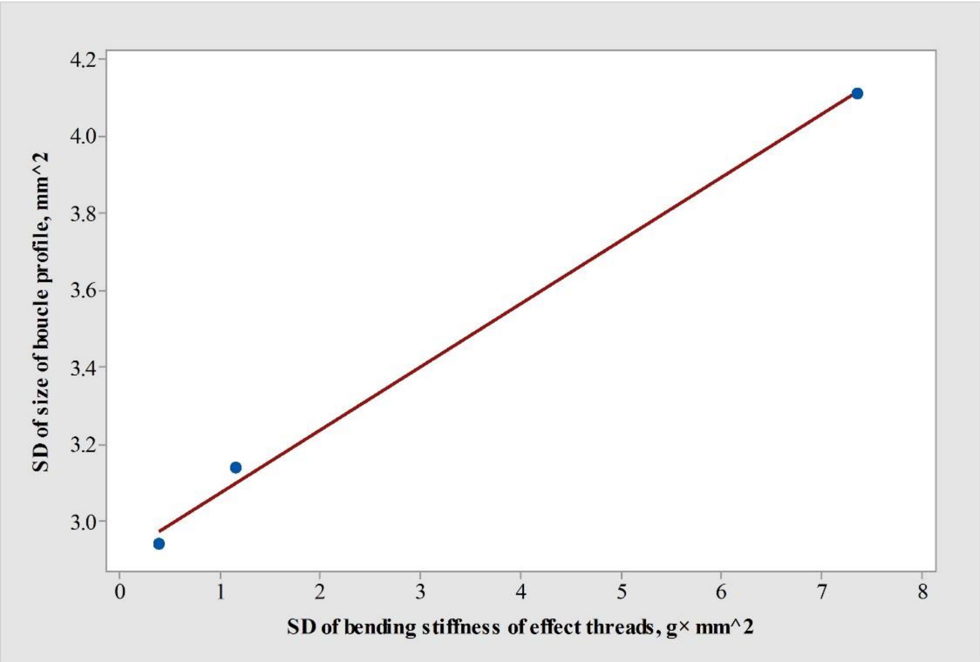


Figure 69: Plot of Effect of Variation in the Stiffness of the Effect Threads on Variation in the Size of Bouclé Profile

Further, the relationship between the variations in bending stiffness of the input threads and variation in the area of the profiles was linear as follows:

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[23] Obtained from response tables of the mean value and standard deviation of the Size of Bouclé Profile

$$SD\ of\ Size\ of\ Boucl\acute{e}\ Profile = 3.00 - 0.0314\, SD_{core} + 0.163\, SD_{effect} \quad (5.19)$$

Where: SD_{core} and SD_{effect} are standard deviations of bending stiffness of the core thread and the effect threads respectively, measured in g mm^2.

This relationship was significant at a confidence level 99%, and the p-value of ANOVA testing was 0.099 %.

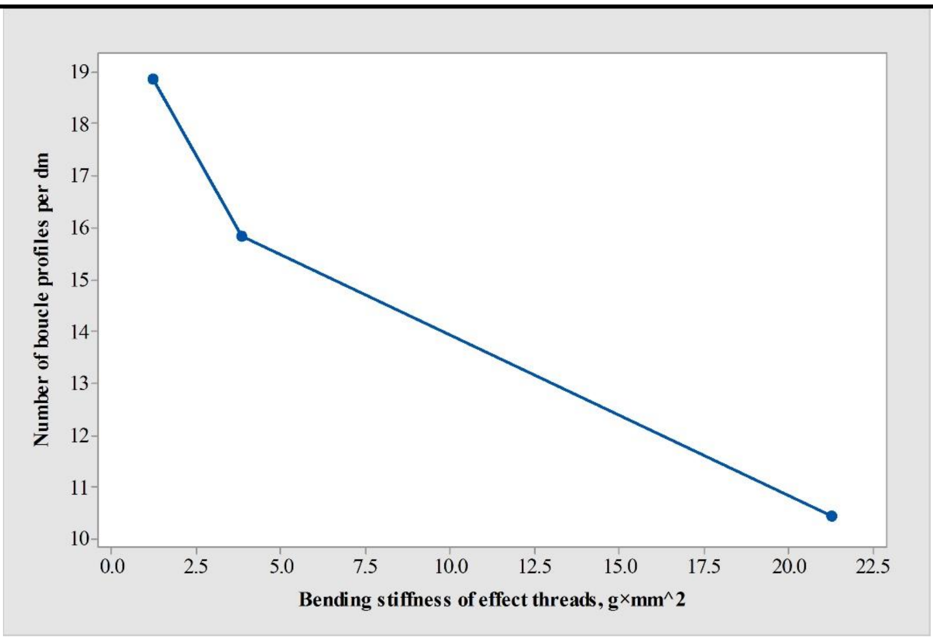
Finally, the analysis showed that an interaction between the variability of B_e and B_c happened only when using the stiffest core thread (C3). Further, when the stiffest core thread was used the variation in the Size of Bouclé Profile did not change, even though B_e was changed considerably. Such a result may be important in order to control the variability in the Size of Bouclé Profiles by using a relatively stiff core thread.

5.17.4 Conclusions Regarding the Size of Bouclé Profile

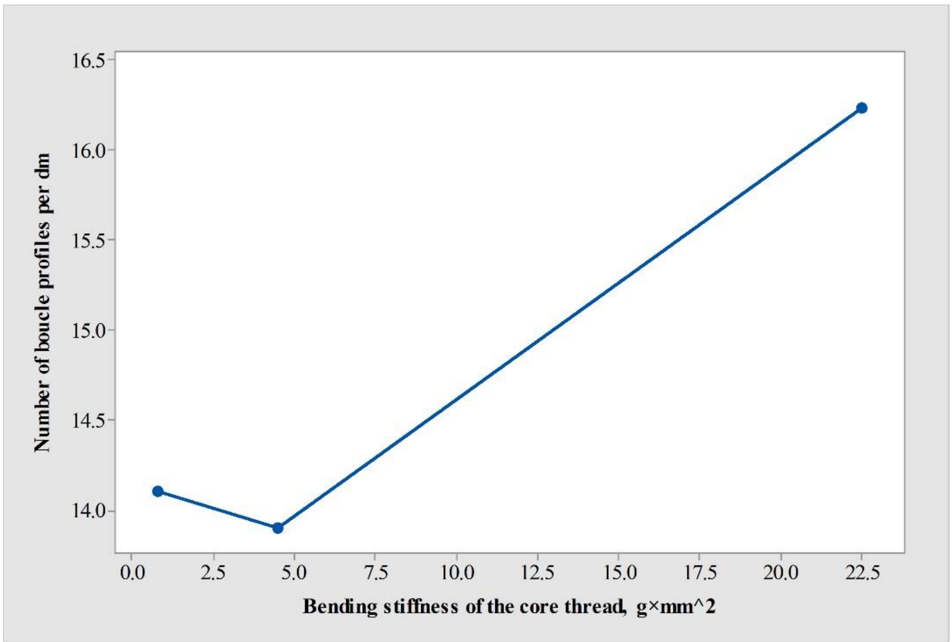
- the stiffer the effect threads of boucle yarn (up to 21 g mm^2) the larger the bouclé profiles (up to approximately 14 mm^2). This relationship was linear and significant at a 99 % confidence level;
- The higher the variation in the bending stiffness of the effect threads (up to SD= 7 g mm^2) the higher the variability in the Size of Bouclé Profile (up to SD ≈ 4 mm^2). This relationship was also linear and significant at a 99 % confidence level; and
- When the core threads were extremely stiff (e.g. B≈22 g mm^2), bouclé profiles were consistent in size, with a low level of variation less than 3 mm^2, whatever was the stiffness of the effect threads;

5.17.5 Influence of the Factors on Number of Bouclé Profiles

Figure 70 demonstrates the influence of bending stiffness of the core thread and bending stiffness of the effect threads and on the Number of Bouclé Profiles.



(a)



(b)

Figure 70: Plots of Main Effect of the Factors on the Number of Bouclé Profiles; (a): Stiffness of the Effect Thread, (b): Stiffness of the Core Thread

Figure 70 (a) confirms that B_e was the main factor which affected the Number of Bouclé Profiles. This is because when B_e increased, from 1.201 to 3.859, and then to 21.279 g mm^2, the Number of Bouclé Profiles decreased steadily from 18.87 to 15.83, and then to 10.43 profile per dm. Moreover, Figure 70 (b) indicates that the bending stiffness of the core thread had a weaker contribution to the Number of Bouclé Profiles. Almost 30 times increase in the B_c value, from 4.507 to 22.514 g mm^2, brought about only two extra bouclé profiles per dm. The total effect of these two factors represented a regression model as follows:

$$Number\ of\ Bouclé\ Profiles\ = 16.9\ +\ 0.108\, B_c -\ 0.362\, B_e \qquad (5.20)$$

This relationship was significant at a 99% confidence level and the p-value of the ANOVA testing was 0.006.

Finally, the analysis showed that an interaction between B_e and B_c related to the Number of Bouclé Profiles happened only when using the most flexible core thread with the stiffest effect threads. This is because when the stiffest effect threads were combined with a flexible core thread, the latter may have been pressed by the former during the manufacture of the intermediate product, within the hollow spindle. So, the flexible core thread was not able to resist the influence of stiffer effect threads. Subsequently, the stiffer effect threads made bouclé profiles to the size and number which were permissible by other parameters (i.e. the overfeed ratio, number of wraps, speeds, etc.). Therefore, the Number of Bouclé Profiles was as low as 9.6 per dm. In contrast, a stiff core thread may have shown more resistance to the influence of the effect threads. It may have affected the freedom of the effect threads within hollow spindle. Consequently, the effect threads may have become confined with an additional factor, other than the aforementioned parameters. Therefore, this allowed the binder to reduce the Size of Bouclé Profiles; thus, increasing the number of small profiles per unit length.

5.17.6 Influence of the Variability of the Factors on Variation in the Number of Bouclé Profiles

The variability of the Number of Bouclé Profiles may be originated in part from the variability of the factor levels and in another part from the process itself. It seemed, from Figure 71 (a), that using the most flexible effect threads might have been a reason for obtaining a high level of variation in the Number of Bouclé Profiles. Additionally, increasing the variation in the bending stiffness of the effect threads by approximately three times (from level 1 to level 2) reduced the variation in the Number of Bouclé Profiles by almost half. Moreover, Figure 71 (b) shows that increasing the variation in bending stiffness of the core thread led to an increase in the variation in the Number of Bouclé Profiles.

Importantly, the analysis showed that an interaction between the bending stiffness of the core thread and the bending stiffness of the effect threads related to the variability of the Number of Bouclé Profiles happened only when using the most flexible core thread.

The CV% of the production process regarding the Number of Bouclé Profiles, was 20.8 %. This high variability may have been attributed to several reasons as follow:

1. The stiffest core thread which had a considerable level of variability, i.e. SD= 6.75 g mm^2.
2. As the analysis showed, the mean value of flexural stiffness of the effect threads may have contributed to such a high level of variation in the number of profiles.
3. The spinning geometry was found not to be stable and not to have a steady-state situation. Instead, there was variation in the number and geometry of the effect-thread helices which affected the constancy of the Number of Bouclé Profiles. The source of this variability may be the process and random variation. This is because the variation in stiffness of the effect threads affects only the variation in the Size of Bouclé Profiles, but not the variation in the Number of Bouclé Profiles.
4. Furthermore, the relatively soft effect threads had *weak* resistance to the process variation; thus, they were affected more than stiffer effect threads by the process variation. Eventually, a considerable alteration in the Number of Bouclé Profile was

inevitable. Nonetheless, using relatively stiff effect threads may reduce the influence of process variation.

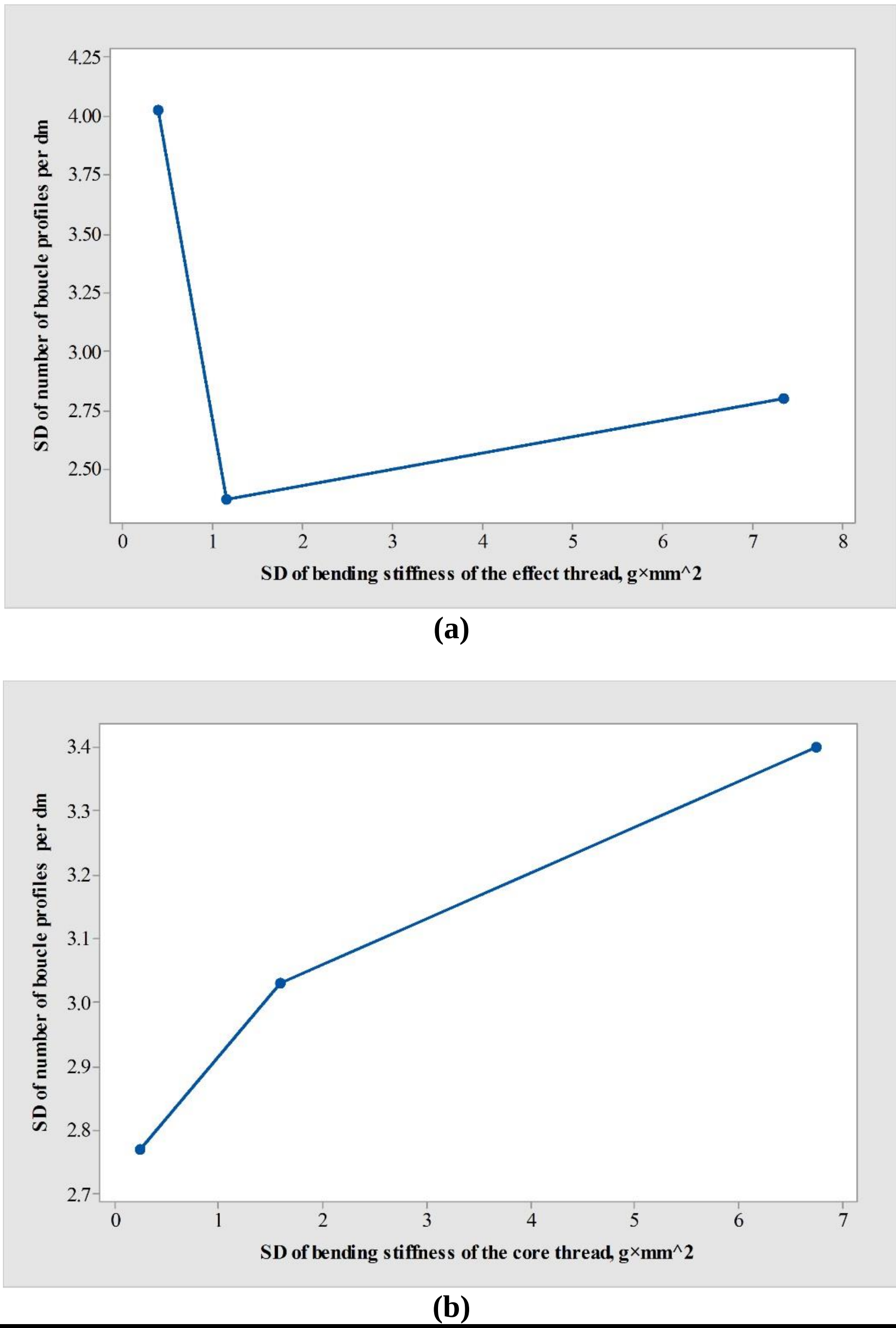


Figure 71: Main-Effect Plots of Variation of the Factors on the Variation in Number of Bouclé Profiles; (b): Stiffness of the Effect Threads, (b): Stiffness of the Core Thread

In all case, designers of fancy yarn may want a bouclé yarn with high level of variation in its structure. A direct advantage to this approach was avoiding ‘pattern’ in final fancy fabrics and garments made of those bouclé yarns.

5.17.7 Conclusions Regarding the Number of Bouclé Profiles

- Increasing the bending stiffness of the effect threads from 1.201 to 21.279 g mm^2, decreased the number of bouclé profiles decreased from 18.87 to 10.43 per decimetre. So, the stiffer the effect threads of boucle yarns, the lower the number of bouclé and semi-bouclé profiles.
- A linear significant relationship was obtained between the average value of number of bouclé profiles and the stiffness of the threads at a 99% confidence level.
- The average value of flexural stiffness of the effect threads was responsible for the variability in Number of Bouclé Profiles.
- Using relatively flexible effect threads (e.g. B_e=1.2 g mm^2) may have contributed to high levels of variation in the Number of Bouclé Profiles (e.g. SD≥ 4 profile per decimetre).
- Only when a stiff core thread (B_c=22 g mm^2) was used, the average value of the Number of Bouclé Profiles increased slightly by 2 profiles per decimetre.

5.17.8 Influence of the Factors E and C on the Absolute Fancy Bulkiness of Bouclé Yarn

The influence of the bending stiffness of the effect threads (B_e) and the bending stiffness of the core thread (B_c) on the Shape Factor of Fancy (Bouclé) Yarn is shown in Figure 72. This figure shows that there was a considerable change in the ShF when B_e and B_c changed. The effect threads were twice as much as the core thread to contribute to the ShF. Further, Figure 72 (a) indicates that the stiffer the effect threads the lower the ShF, that is, the lower the Absolute Fancy Bulkiness of Bouclé Yarn. Although the core thread did not have a clear relationship with the ShF, but Figure 72 (b) shows that using the stiffest core thread increased the ShF.

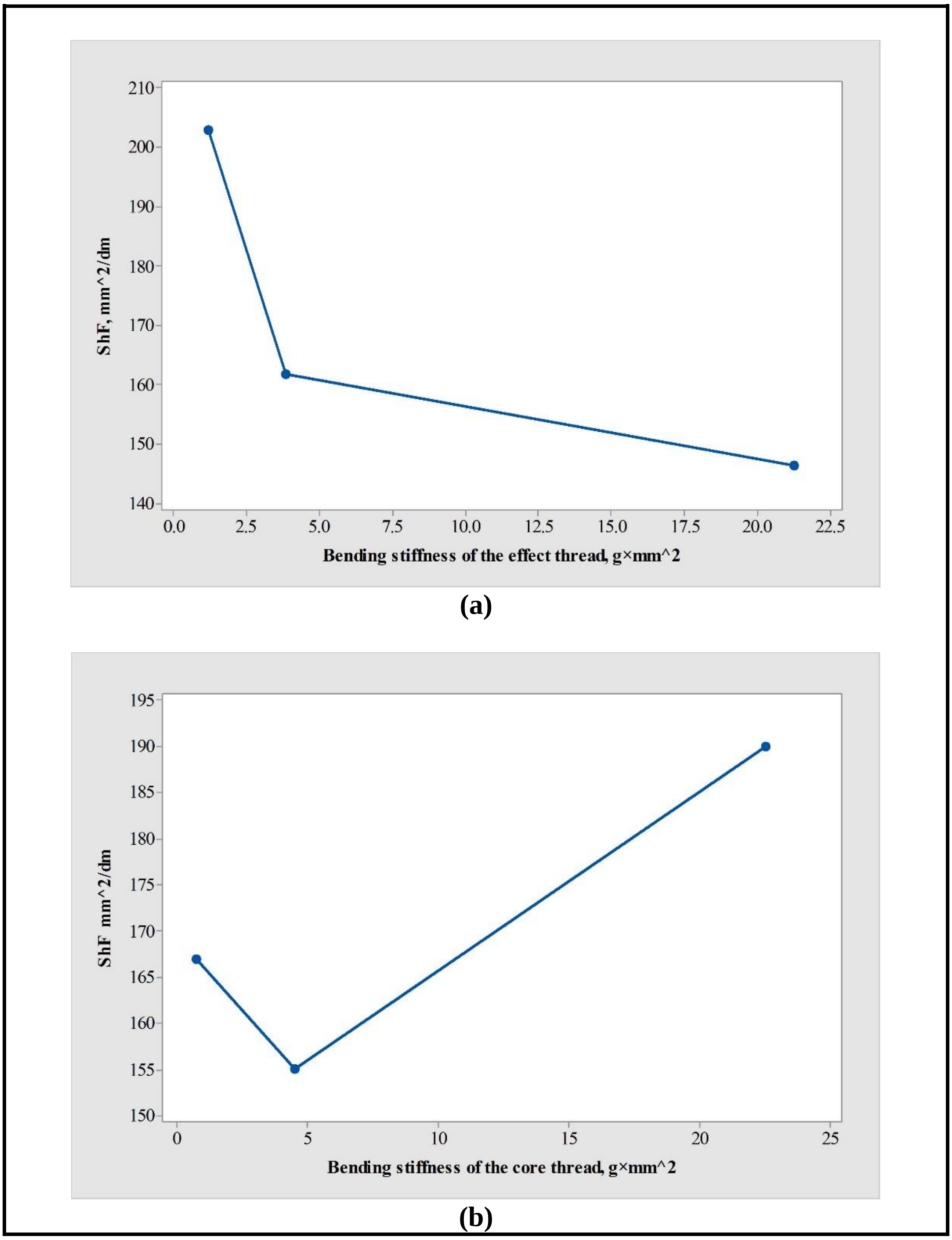


Figure 72: Plot of Main-Effect of Factors E and C on the Shape Factor of Bouclé Yarn

The data of these plots were combined to build a regression model as follows:

$$ShF = 177 + 1.32\, B_c - 2.13\, B_e \tag{5.21}$$

The results of the ANOVA testing confirmed that this model was significant at a confidence level 99% (i.e. p-value was 0.094).

The plot of interaction of B_e and B_c related to the Absolute Fancy Bulkiness of Bouclé Yarn is given in Figure 73. This figure indicates that interactions happened when using the medium-stiffness core thread. Further, the lowest values of the ShF resulted when using the stiffest effect thread.

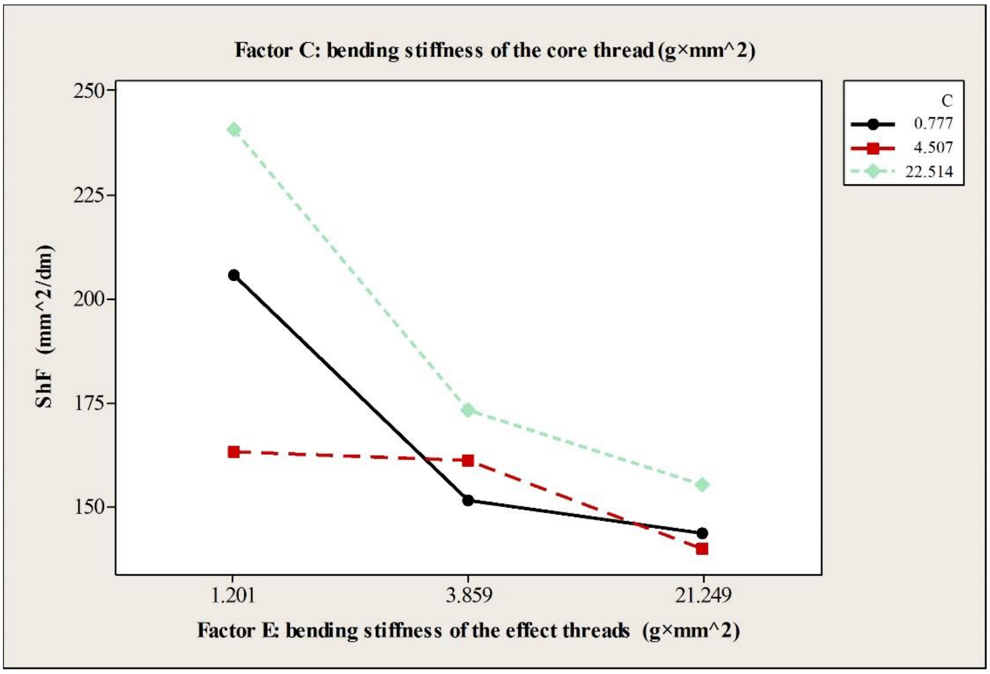


Figure 73: Plot of Interaction of Factors Regarding the Shape Factor of Bouclé Yarn

5.17.9 Conclusions Regarding the Shape Factor of Fancy (Bouclé) Yarn

- The stiffer the effect threads of bouclé yarns, the lower the value of the Shape Factor of Bouclé Yarn; thus, the smaller the Absolute Fancy Bulkiness of Bouclé Profiles. This relationship was linear and significant at a confidence level 99 %.
- Since the core thread had weak contributions, except when its bending stiffness was more than 20 g mm^2, to the structural properties of multi-thread bouclé yarn, it can be discarded from investigation when making bouclé yarns.

5.17.10 Testing the Regression Models to Confirm the Results

Properties of the material used in these confirmation trials are given in Table 15. The results of the confirmation procedure are given in Table 47 for models 5.18, 5.19, 5.20 and 5.21. Based on the value of ShF, a remarkable agreement between and real values and the values predicated by model 5.21 was achieved. The deviation for the confirmation yarn 1 was (155-166)/166 ×100 = -06.6 % and the deviation for confirmation yarn 2 was approximately zero.

Table 47: Results of Model Testing: Comparison between Theoretically Expected Values and Actual Values of Properties of Bouclé Yarn

Bouclé Yarn Property	Confirmation Yarn 1			Confirmation Yarn 2		
	Predicted Value	Actual Value	Deviation from Predicted Value %	Predicted Value	Actual Value	Deviation from Predicted Value %
Size of bouclé profile, mm^2	11.71	12.23	4.44	12.1	13.35	10.3
SD of size, mm^2	3.23	2.75	-14.86	3.43	3.15	-8.16
Number of bouclé profiles, dm^{-1}	14.6	12.7	-13	13.6	11.9	-12.5
SD of number, dm^{-1}	2.9	3.4	17.2	2.8	2.4	-14.28
ShF, $mm^2\ dm^{-1}$	166	155	-6.62	159	159	0

Images of all bouclé and semi-bouclé yarns made for this experiment are given in Figure 74.

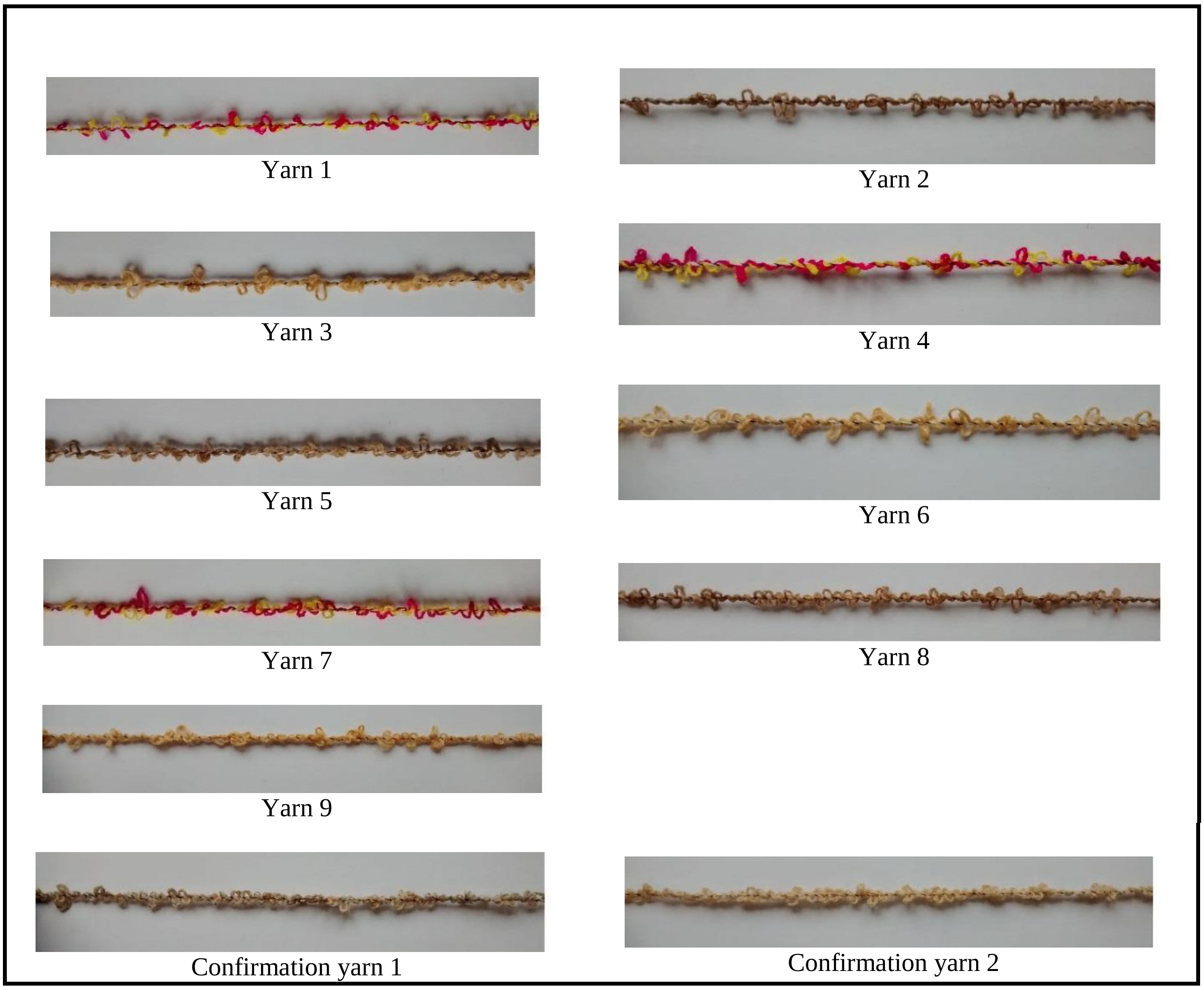


Figure 74: Image of the Bouclé Yarns of the Experimental Design of this Experiment

The order of the yarns corresponds to the standard order of the experiment trials. Figure 74 shows that the fancy yarns were different from each other in structure. This is because the structure of yarns 1, 2, 4, 6 and 7 appeared to have regular distribution of the bouclé profiles along the yarns axes. Further, yarn 5 and 9 had bouclé profiles and dense and compact sigmoidal sections. Furthermore, yarn 3 had irregular distribution of the bouclé profiles which were clustering on each other. Finally, yarn 8 had small bouclé profiles and wide sigmoidal sections, while the two confirmation yarns had a very compact structure.

Chapter 6: Conclusions and Recommendations

Multi-thread bouclé and semi-bouclé yarns, their structure and their manufacturing process on hollow-spindle machines were studied using mainly an objective approach. It was possible to achieve the aims and objectives of this research, and it was concluded that:

- Regarding the graphical and mathematical modelling of the structure of multi-thread fancy yarn:

The structure of multi-thread fancy yarn, including bouclé, was modelled graphically as a sine wave connected with a helical sigmoid. The model had three components, and those were the binder, the core and the effect. Such a graphical model was accounted for mathematically, using trigonometry and calculus. The parameters of the final mathematical model were the length of the effect thread, the number of wraps and the overfeed ratio. That mathematical model predicted the length of the effect thread L_e. Such a model was universal for doubled fancy yarns, including bouclé yarns, wavy yarns, gimp yarns, spiral yarns, irregular overfed yarns and their commercial derivatives and variants. The model was tested on 15 variants of multi-thread of fancy yarn, and it was significant at a confidence level 99%. Furthermore, the correlation coefficient (r) between the theoretical values and the experimental values of L_e was r=0.90.

- Regarding the study of the spinning geometry of multi-thread fancy yarn in the First Spinning Zone of hollow-spindle spinning machines (or fancy twisters):

It was concluded that the effect thread must form helices around the core thread in this zone as a pre-condition to make a multi-thread fancy yarn. Furthermore, more helices in that zone may result in a high number of bouclé profiles, while large helices may result in large bouclé profiles. Therefore, a simple mathematical model was introduced to account for the effect-thread helices. The model indicated that the radius of helices was related to the overfeed ratio of the effect thread, the length of the First Spinning Zone and the number of the helices formed.

- Regarding the factors which may affect the effect-thread helices in the First Spinning Zone:

The conclusion of the experimental work was that increasing the overfeed ratio resulted in an increase to radius and size of the helices. However, the overfeed ratio did not affect the number of the helices. Instead, the number of helices was increasing by increasing the rotational speed of the hollow spindle. However, increasing the rotational speed reduced the radius and size of the helices. It was also found that increasing the rotational speed from RS=2000 to 9000 rpm increased the number of the effect-thread helices from 1 up to 10 helices, but made them narrower and touching the core thread, similar to a screw. Moreover, the thickness and stiffness of the effect thread affected the number of the helices. For example, a thin and soft effect thread (an 83 tex lambswool thread with bending stiffness B=0.594 g mm^2) always resulted in a low number of large helices in comparison with a thick and stiff effect thread (an R118/2 tex, 2-ply wool thread with bending stiffness B=4.2 g mm^2) for several values of the rotational speed.

- To find a method for the estimation of the bending stiffness of the input threads:

The Quasi-static Beam Method using a bending frame was used because it gave the mean and the standard deviation of the total bending stiffness of input yarns. This method was applied with the help of the digital image analysis technique. This method was accurate and consistent, and it showed that the variability of bending stiffness of yarns, whether they are singles, two-ply or three-ply, may be as high as CV=52.5%. In all cases, using this method with the help of ordinary commercial rulers, instead of the digital image technique, may give quicker, more practical, but less accurate results.

- In terms of assessment of the influence of bending stiffness of the effect thread on the structure of multi-thread bouclé yarns:

It was concluded that a stiff effect thread may result in low number of large bouclé profiles, in comparison with a soft effect thread. For instance, increasing the stiffness of the effect threads from 1.5 to 18 g mm^2 increased the average Size of Bouclé Profile from 14.74 up to 18.88 mm^2. However, the average Number of Bouclé Profiles decreased from 14.27 down to 6.46 dm^{-1}. Furthermore, increasing the variation in the bending stiffness of the effect threads from approximately SD_B =0.5 to 7.5 g mm^2 increased the variability in Size of Bouclé Profile from approximately 2.5 up to 4 mm^2.

- Regarding the influence of bending stiffness of the core thread on the structure of multi-thread bouclé yarns:

Unless the core thread was extremely stiff, e.g. $B_C \approx 20$ g mm^2, the core thread did not affect the structure of multi-thread bouclé yarns. However, at that high value, the core thread increased the number of the bouclé profiles by 2 per decimetre and made the profiles more consistent in size.

- With regard to the dimensions of the spinning triangle:

It was concluded that the width of the spinning triangle, i.e. distance between the core thread and the effect thread, at the beginning of the First Spinning Zone had no influence on the structure of bouclé yarns.

- When studying the Tension of the core thread, while making multi-thread fancy yarns on hollow-spindle machines:

It was concluded that this factor was important, because decreasing the levels of Tension from 21 grams to approximately 0 increased the Number of Bouclé Profiles from 22 up to 36 profiles per dm. It also made wider spiral sections or wavy corrugations between bouclé profiles. Further, it increased the Circularity Ratio of Bouclé Profile from CR≈35 up to 64%. Furthermore, it reduced both the mean value and variation of the Size of Bouclé Profile from approximately 44 down to 20 mm^2. However, when the Tension was 21 grams, the machine did not make any bouclé yarn. So, the final result on fancy yarns was that low level of Tension improved the quality and appearance of bouclé yarns. Further, it was possible to make a bouclé yarn using only one effect thread when the real overfeed ratio was only 50% in comparison with the core thread. Consequently, it was useful to reduce the usage of resources and to reduce costs while improving the quality of the ultimate bouclé yarns.

- With regard to the impact of the overfeed ratio on the structure of multi-thread bouclé yarns:

It was concluded that increasing the overfeed ratio from 180 up to 260% increased the Size of Bouclé Profile from 13.5 to 23.6 mm^2 and increased the Number of Bouclé Profiles from 12 to 16.4 dm^{-1}. Therefore, it increased the Fancy Bulkiness of Bouclé Yarn from 162 up to 535 $mm^2\ dm^{-1}$. However, it decreased the Circularity Ratio of Bouclé Profile from CR≈ 60 to 50 %.

- With regard to the impact of the number of wraps on the structure of multi-thread bouclé yarns:

It was concluded that increasing the number of wraps from 160 to 220 wpm made reductions to the Size of Bouclé Profile from 21.6 to 15 mm^2, but also reduced its variability from CV≈35 to 20 %. Therefore, the bouclé profiles were more consistent in size. However, the number of wraps did not affect Number of Bouclé Profiles.

- In terms of the interaction between the overfeed ratio and the number of wraps:

It was concluded such an interaction can be studied using the Structural Ratio of Multi-thread Fancy Yarn (SR). Further, a value of SR in the range 0.88 and 1.2 wpm may result in a good quality bouclé yarn in terms of making high Number of Bouclé Profiles with suitable values and consistency of the Size of Bouclé Profiles.

- With regard to the variability of the machine:

The variability resulting from the hollow-spindle machine was accepted because running the machine over 205 minutes did not increase the variation of the Shape Factor of Bouclé Yarn by more than 12 %.

- In terms of the accuracy of this research:

It was concluded that significant regression models may be used to account for the aforementioned relationships at confidence levels exceeding 90%. This is because regression models were found to account for the relationships between:

- The bending stiffness of the effect threads and the Number of Bouclé Profiles at a 90 % confidence level;
- The bending stiffness of the effect threads and the Size of Bouclé Profile at a 90% confidence level;
- The variation in bending stiffness of the effect threads and the variation in the Size of Bouclé Profiles at a 99% confidence level;
- The overfeed ratio and the Size of Bouclé Profile at a 99% confidence level;
- The overfeed ratio and the Number of Bouclé Profiles at a 99% confidence level;
- The overfeed ratio and the Shape Factor of Bouclé Yarn at a 99% confidence level;
- The overfeed ratio and the Circularity Ratio of Bouclé Profile at a 99% confidence level;
- The number of wraps and the Size of Bouclé Profile at a 99% confidence level;
- The number of wraps and the Shape Factor of Bouclé Yarn at a 99% confidence level.

Therefore, based on this research, it is recommended to make a boucle yarn, using hollow-spindle machines, taking into account the following recommendations:

- The mathematical model of this research should be used to forecast the structure of multi-thread bouclé yarns. This model should also be used to forecast the changes which may happen to the structure of multi-thread bouclé yarns if the number of wraps or the overfeed ratio were altered due to changes in the production or the manufacturing conditions;

- The First Spinning Zone should be monitored and controlled in order to control the structure of the ultimate multi-thread bouclé yarns.
- The ultimate multi-thread bouclé yarns should have high number of bouclé and semi-bouclé profiles even when the size of those profiles is relatively small;
- One effect thread should be used where it is possible to mainly reduce the costs of the manufacturing process;
- The Tension of the core thread when making a bouclé yarn, using only one effect thread, should be as low as possible, i.e. approximately zero. Such a low level of Tension should allow the core thread to form at least one uniform balloon, or two uniform balloons in some other cases, in the First Spinning Zone of the hollow-spindle machines;
- The bending stiffness of the effect thread should be used as a main property to describe this component along its linear density. This is because selecting a suitable stiffness for the effect thread helps to ensure that the proper structure of bouclé yarns can be made;
- The Quasi-static Beam Method should be used to estimate the bending stiffness of the effect thread(s). It is possible to use calibrated rulers to measure the deflection distances of the threads. However, to obtain precise results, the digital image analysis technique should be used. The specimens of the threads should be measured for bending at a constant length and the number of specimens should be at least 15. The effect thread specimens should be (preconditioned then) conditioned in a standard atmosphere before conducting the test.
- The technique of Design of Experiments (DOE) should be used to study the manufacturing process of multi-thread bouclé yarns in industrial situations where the number of parameters is high.
- A low overfeed ratio should be used as often as possible, even when it is as low as η=1.5% (i.e. Δ=50%);

- Following the selection of a low and suitable overfeed ratio, a low number of wraps should be used so that the structure of the ultimate bouclé yarn is not compact;

- The Structural Ratio of Multi-thread Fancy Yarn should be used to account for the interaction between the overfeed ratio and the number of wraps. The value of the Structural Ratio of Multi-thread Fancy Yarn should be between 0.88 ~ 1.2 wpm in order to make a good-quality bouclé yarn, using only one effect thread.

Chapter 7: Future Work

The research on the structure of multi-thread bouclé yarn can be extended in the future by considering new fields of study. Some of those could be:

- A similar study may be conducted when the boucle yarns are made using the traditional spinning, doubling and twisting system, instead of the hollow-spindle system. During such a study, the general version of the mathematical model of the structure of multi-thread fancy yarn can be applied to forecast the structure of the ultimate bouclé yarns or to forecast the length and usage of the effect thread within the structure.
- The influence of more than one effect thread, i.e. two or three effect threads, on the structure and quality of multi-thread bouclé yarns may be studied using the Design of Experiments (DOE) technique.
- The influence of more than one effect threads when each of them has its own overfeed ratio may also be studied using the DOE technique.
- The influence of two or three effect threads that are different in thickness and/or stiffness, on the structure and quality of bouclé yarns may also be studied using the DOE technique.
- The influence of thickness of the effect threads when their stiffness is the same, and vice versa, on the structure and quality of bouclé yarns may be studied using the DOE.
- A study may be conducted to control the consistency of boucle profiles. This study may be achieved by selecting uniform effect threads in terms of thickness and flexural stiffness or via changing or modifying the manufacturing process.
- Although complicated and complex models are already available, a simple mathematical model for the strength of multi-thread bouclé may be developed. Such a simple model may make the performance of those types of multi-thread fancy yarn easily predictable in advance.

- The physical properties of the structure of multi-thread bouclé yarn, in particular abrasion resistance and compressions resistance, may be studied. This is because those properties may affect the bouclé profiles and their appearance severely.
- A research may be conducted to study the relationship between the structure of multi-thread bouclé yarn and the structure of fancy fabrics made with those bouclé yarns in terms of physical properties, mechanical properties and appearance.
- A similar research may also be conducted to study wavy yarns, gimp yarns, spiral yarns, irregular overfed yarns and their commercial derivatives and variants. This is because those types of multi-thread fancy yarn are already accounted for by the mathematical model of the structure in its universal form. Furthermore, such a study can be conducted when those types of multi-thread fancy yarn are made on the hollow-spindle machines or the traditional spinning, doubling and twisting system.

Appendices

Appendix A: The Results of the Bending Stiffness Measurements

A-1: The Results Using the Initial Bending Frame

Table A-1: Results of Testing Input Yarn 1 for Bending Using the Initial Bending Frame

Input yarn 1, 14	**Acrylic, R72/2 tex, colour: canary and cerise**					
specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	50	0.005	26	2.5	1.325	5.95
2	50	0.005	27	2	1.676	4.97
3	50	0.005	29	3	1.128	8.13
4	55	0.004	29	4	0.886	8.75
5	55	0.004	31	3.5	1.028	8.30
6	55	0.004	32	7	0.514	16.93
7	60	0.005	36	4	1.458	9.46
8	60	0.005	35	5	1.169	11.31
9	60	0.005	36	5.5	1.06	12.91
10	65	0.006	36	5.5	1.616	10.74
11	65	0.006	40	4.5	1.965	10.20
12	65	0.006	38	7	1.274	14.53
13	65	0.005	36	6.5	1.139	12.63
14	65	0.005	37	6	1.238	12.09
15	65	0.006	42	7	1.031	16.93
Average					1.199	11.81
Standard deviation (SD)					0.361	3.62
Coefficient of variation (CV %)					30.098	30.67
Normality test (Anderson-Darling Test): p-value					0.416	

Table A-2: Results of Testing Input Yarn 2 for Bending Using the Initial Bending Frame

Input yarn 2	**Cotton/lambswool, R120/2 tex, undyed**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	60	0.007	30	1.5	5.25	2.86
2	60	0.007	32	1.5	5.389	3.07
3	60	0.007	32	1.5	5.389	3.07
4	65	0.008	35	1.5	7.852	2.86
5	65	0.008	38	5.5	2.163	11.51
6	65	0.008	40	3.5	3.367	7.97
7	70	0.009	37	5.5	2.992	9.46
8	70	0.009	38	4	4.146	7.13
9	70	0.009	42	6	2.778	12.09
10	75	0.010	37	3.5	6.234	5.26
11	75	0.010	31.5	4.5	4.316	5.91
12	75	0.010	37	4	5.455	6.01
13	80	0.010	45	9.5	2.914	15.19
14	80	0.010	41	4.5	5.994	6.58
15	80	0.010	41	8	3.371	11.59
				Average	4.507	7.37
				Standard deviation (SD)	1.592	3.87
				Coefficient of variation (CV %)	35.310	52.54
				Normality test (Anderson-Darling Test): p-value	0.412	

Table A-3: Results of Testing Input Yarn 3 for Bending Using the Initial Bending Frame

Input yarn 3	**Combed cotton, R126/3 tex, Ne=14/3, colour: Amber**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	45	0.006	25	3	1.147	8.53
2	45	0.006	31	1.5	2.121	6.12
3	45	0.006	27	2.5	1.377	7.91
4	50	0.007	30	3	1.575	8.53
5	50	0.007	25	2	2.278	4.57
6	50	0.007	32	2.5	1.849	7.91
7	55	0.007	31	5.5	1.145	12.91
8	55	0.007	31	5	1.259	11.77
9	55	0.007	32	5.5	1.146	13.45
10	60	0.007	33	5.5	1.481	11.51
11	60	0.007	38	6	1.338	15.26
12	60	0.007	35	6.5	1.259	14.57
13	55	0.007	33	4	1.572	10.30
14	55	0.007	37	2	2.972 [24]	6.34
15	55	0.007	28	4	1.529	8.43
				Average	1.603	9.87
				Standard deviation (SD)	0.512	3.25
				Coefficient of variation (CV %)	31.915	32.89
				Normality test (Anderson-Darling Test): p-value	0.013	

[24] If this value was ignored, it would results in normally distributed sample with p-value=0.072 of the same test; apart from this it was kept within the results.

Table A-4: Results of Testing Input Yarn 4 for Bending Using the Initial Bending Frame

Input yarn 4	**Natural wool, R195/2 tex**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	65	0.013	38	3.5	5.523	7.39
2	65	0.013	45	2.5	7.087	7.13
3	65	0.013	41	2	9.497	4.76
4	70	0.014	48	3	8.0256	7.77
5	70	0.015	46	3.5	7.643	8.30
6	70	0.013	46	4	5.796	9.46
7	75	0.016	45	8	4.556	14.93
8	75	0.016	51	6	5.687	14.04
9	75	0.016	41	3.5	10.378	5.88
10	80	0.016	50	6	7.291	11.31
11	80	0.016	42	6.5	6.703	9.71
12	80	0.016	39	6	7.015	8.33
13	85	0.017	45	6.5	8.567	9.23
14	85	0.017	48	8	7.059	12.20
15	85	0.017	48	7.5	7.53	11.46
Average,					7.22	9.46
Standard deviation (SD)					1.53	2.88
Coefficient of variation (CV %)					21.13	30.44
Normality test (Anderson-Darling Test): p-value					0.700	

Table A-5: Results of Testing Input Yarn 5 for Bending Using the Initial Bending Frame

Input yarn 5	**Lambswool, R120/2 tex, colour: Honeysuckle**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	60	0.008	30	3	3	5.71
2	60	0.008	28	3	2.88	5.36
3	60	0.008	29	2.5	3.534	4.61
4	65	0.008	38	6	1.982	12.53
5	65	0.008	34	4.5	2.593	8.26
6	65	0.008	37	3	3.964	6.12
7	70	0.009	40	5	5.571	9.46
8	70	0.009	34	4.5	3.517	7.13
9	70	0.009	40	6	2.785	11.31
10	75	0.01	40	5.5	4.101	8.93
11	75	0.01	48	6.5	3.429	13.54
12	75	0.01	42	7	3.257	11.98
13	70	0.009	37	6.5	2.531	11.14
14	70	0.009	36	5	3.257	8.37
15	70	0.009	39	4.5	3.7	8.26
Average					3.340	8.85
Standard deviation (SD)					0.839	2.78
Coefficient of variation (CV %)					25.123	31.45
Normality test (Anderson-Darling Test): p-value					0.335	

Table A-6: Results of Testing Input Yarn 6 for Bending Using the Initial Bending Frame

Input yarn 6	**Wool/polyamide, R120/2 tex, colour: Aroma**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta} = \mathbf{arctan}(\frac{\boldsymbol{y}}{\boldsymbol{L}-\boldsymbol{x}})$
1	60	0.009	32	1.5	6.929	3.07
2	60	0.009	33	2.5	4.189	5.29
3	60	0.009	35	2	5.263	4.57
4	65	0.009	39	4.5	2.965	9.82
5	65	0.009	33	2	6.483	3.58
6	65	0.009	35	2	6.625	3.81
7	70	0.009	35	2.5	6.431	4.09
8	70	0.009	45	5	3.254	11.31
9	70	0.009	45	3.5	4.649	7.97
10	75	0.01	41	6.5	3.492	10.82
11	75	0.01	41	7	3.243	11.63
12	75	0.01	42	8	2.849	13.63
13	75	0.01	42	5	4.559	8.62
14	75	0.01	44	3	7.613	5.53
15	75	0.01	49	7.5	2.936	16.09
Average					4.765	7.99
Standard deviation (SD)					1.671	4.10
Coefficient of variation (CV %)					35.06	51.28
Normality test (Anderson-Darling Test): p-value					0.082	

Table A-7: Results of Testing Input Yarn 7 for Bending Using the Initial Bending Frame

Input yarn 7	**Lambswool/viscose, 60 %/40 %, R120/2 tex, colour: Gretna Green**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	60	0.007	29	2	3.69	3.69
2	60	0.007	39	2	5.44	5.44
3	60	0.007	35	1	2.29	2.29
4	65	0.008	37	4	8.13	8.13
5	65	0.008	36	3.5	6.88	6.88
6	65	0.008	42	2	4.97	4.97
7	70	0.008	36	3.5	5.88	5.88
8	70	0.008	45	4.5	15.71	15.71
9	70	0.008	44	5	10.89	10.89
10	75	0.009	40	5	8.13	8.13
11	75	0.009	39	4	6.34	6.34
12	75	0.009	38	2.5	3.87	3.87
13	80	0.010	46	8	13.24	13.24
14	80	0.010	42	5.5	8.24	8.24
15	80	0.010	49	5.5	10.06	10.06
Average					4.593	7.58
Standard deviation (SD)					1.639	3.68
Coefficient of variation (CV %)					35.683	48.51
Normality test (Anderson-Darling Test): p-value					0.018	

Table A-8: Results of Testing Input Yarn 8 for Bending Using the Initial Bending Frame

Input yarn 8	**Wool/Cotton 50/50, R163/2 tex, Colour: Snapdragon**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	70	0.011	32	3	6.199	4.51
2	70	0.011	44	1.5	13.402	3.30
3	70	0.011	44	2.5	8.042	5.49
4	70	0.011	38	2	10.135	3.58
5	75	0.012	41	4	6.811	6.71
6	75	0.012	48	6	4.458	12.53
7	75	0.012	12	1.5	4.052	1.36
8	75	0.012	40	3.5	7.733	5.71
9	80	0.012	47	3	9.238	5.19
10	80	0.012	42	4	6.807	6.01
11	80	0.012	47	6	4.619	10.30
12	80	0.012	34	3	9.9527	3.73
13	90	0.015	45	4.5	12.656	5.71
14	90	0.015	45	3	18.984	3.81
15	90	0.015	48	8	7.308	10.78
Average					8.693	5.92
Standard deviation (SD)					3.968	3.07
Coefficient of variation (CV %)					45.642	51.96
Normality test (Anderson-Darling Test): p-value					0.159	

Table A-9: Results of Testing Input Yarn 9 for Bending Using the Initial Bending Frame

Input yarn 9	**Wool/Nylon, Colour: Camel, R120/2 tex**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	60	0.007	27	3.5	2.104	6.05
2	60	0.007	36	3.5	2.332	8.30
3	60	0.007	37	2	4.056	4.97
4	65	0.007	32	3.5	2.837	6.05
5	65	0.008	34	3.5	3.334	6.44
6	65	0.008	41	2	5.844	4.76
7	70	0.008	26	4	2.797	5.19
8	70	0.008	43	3.5	4.211	7.39
9	70	0.008	47	4.3	3.118	10.59
10	75	0.0095	33	3.5	5.483	4.76
11	75	0.0095	45	5	4.328	9.46
12	75	0.0095	45	6	3.607	11.31
13	80	0.01	46	6.5	4.621	10.82
14	80	0.01	43	8.5	3.305	12.94
15	80	0.01	43	5	5.487	7.70
Average					3.831	7.78
Standard deviation (SD)					1.164	2.67
Coefficient of variation (CV %)					30.376	34.34
Normality test (Anderson-Darling Test): p-value					0.628	

Table A-10: Results of Testing Input Yarn 10 for Bending Using the Initial Bending Frame

Input yarn 10	**Linen/Cotton, Colour: Sand, R144/2 tex**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	65	0.009	40	4.5	2.948	10.20
2	65	0.009	40	7	1.895	15.64
3	65	0.009	45	4	3.066	11.31
4	60	0.009	37	3	3.476	7.43
5	60	0.009	32	4	2.598	8.13
6	60	0.009	39	4.5	2.262	12.09
7	55	0.008	45	1	4.602	5.71
8	55	0.008	28	6	1.165	12.53
9	55	0.008	28	3	2.33	6.34
10	60	0.009	31	6.5	1.581	12.63
11	60	0.009	37	3.5	2.98	8.65
12	60	0.009	38	3.5	2.949	9.04
13	65	0.011	34	5	3.209	9.16
14	65	0.011	33	5.5	2.881	9.75
15	65	0.011	37	6.5	2.515	13.07
Average					2.697	10.11
Standard deviation (SD)					0.823	2.75
Coefficient of variation (CV %)					30.505	27.20
Normality test (Anderson-Darling Test): p-value					0.476	

Table A-11: Results of Testing Input Yarn 11 for Bending Using the Initial Bending Frame

Input yarn 11	**Lambswool Nm 1/12s, 83 tex, Colour: Rose**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	40	0.0031	20	2	0.516	5.71
2	40	0.0031	33.5	1	0.624	8.75
3	40	0.0034	23.5	2	0.59	6.91
4	45	0.0032	18	3	0.427	6.34
5	45	0.0033	13.5	1.5	0.631	2.73
6	45	0.0035	26	2.5	0.691	7.50
7	50	0.0035	33.5	3.5	0.64	11.98
8	50	0.0039	34.5	3	0.809	10.95
9	50	0.0035	29	4	0.592	10.78
10	45	0.0034	33	2	0.709	9.46
11	45	0.004	19	2	0.758	4.40
12	45	0.003	29.5	2.5	0.588	9.16
13	40	0.003	17	1.5	0.655	3.73
14	40	0.003	19	0.5	1.813	1.36
15	40	0.003	28	1.5	0.627	7.13
Average					0.711	7.13
Standard deviation (SD)					0.318	3.14
Coefficient of variation (CV %)					44.747	44.08
Normality test (Anderson-Darling Test): p-value					<0.005	

Table A-12: Results of Testing Input Yarn 12 for Bending Using the Initial Bending Frame

Input yarn 12	**Pure wool, quality: Glenshear, R120/2 tex, colour: Fawn**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\boldsymbol{\theta} = \mathbf{arctan}(\frac{y}{L-x})$
1	60	0.009	35	2	5.263	4.57
2	60	0.009	35	2.5	4.211	5.71
3	60	0.009	33	2.5	4.19	5.29
4	70	0.010	38	7.5	2.457	13.19
5	70	0.010	40	5.5	3.376	10.39
6	70	0.010	37	8.5	2.151	14.44
7	75	0.010	52	4.5	4.645	11.07
8	75	0.010	40	4	5.638	6.52
9	75	0.010	37	3.5	6.234	5.26
10	75	0.010	44	8.5	2.687	15.33
11	80	0.009	49	6.5	3.811	11.84
12	80	0.011	50	9.5	3.166	17.57
13	80	0.011	51	6.5	4.587	12.63
14	90	0.012	50	11.5	4.106	16.04
15	90	0.012	52	12	3.948	17.53
16	90	0.011	53	9	4.822	13.67
Average					4.006	11.38
Standard deviation (SD)					1.116	4.58
Coefficient of variation (CV %)					27.847	40.22
Normality test (Anderson-Darling Test): p-value					0.968	

Table A-13: Results of Testing Input Yarn 13 for Bending Using the Initial Bending Frame

Input yarn 13	**Stiff acrylic, 140 tex, colour: beige**					
specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	100	0.014	62	5.5	13.633	8.24
2	100	0.014	58	3	25.274	4.09
3	100	0.014	62	5	14.996	7.50
4	110	0.016	72	6	18.505	8.97
5	110	0.016	68	5.5	20.758	7.46
6	110	0.016	54	4.5	24.412	4.59
7	120	0.017	61	7.5	20.561	7.24
8	120	0.017	75	4.5	34.863	5.71
9	120	0.017	80	5.5	27.474	7.83
10	120	0.018	66	5	33.52	5.29
11	125	0.018	78	9.5	19.775	11.43
12	125	0.018	67	6.5	28.96	6.39
13	125	0.018	75	7.5	25.312	8.53
14	130	0.018	75	12	17.848	8.04
15	130	0.018	80	14	15.164	12.31
Average					22.515	8.66
Standard deviation (SD)					6.759	3.75
Coefficient of variation (CV %)					30.022	43.25
Normality test (Anderson-Darling Test): p-value					0.607	

Table A-14: Results of Testing Input Yarn 15 for Bending Using the Initial Bending Frame

Input yarn 15	**Cotton, R72/3 tex, (Andy's cotton), colour: Lt. Camel**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	40	0.003	25	1	0.683	3.81
2	40	0.003	27	1.5	0.651	6.58
3	40	0.003	27	1.5	0.651	6.58
4	45	0.003	26	2.5	0.592	7.50
5	45	0.003	27	2	0.738	6.34
6	45	0.003	24	1.5	0.974	4.09
7	50	0.004	27	4.5	0.596	11.07
8	50	0.004	26	3.5	0.757	8.30
9	50	0.004	30	2.5	1.08	7.13
10	55	0.005	27	3	1.43	6.12
11	55	0.005	32	4.5	1	11.07
12	55	0.005	32	8	0.563	19.18
13	55	0.004	31	5.5	0.654	12.91
14	55	0.004	31	4	0.899	9.46
15	55	0.004	31	6	0.599	14.04
Average					0.791	8.94
Standard deviation (SD)					0.242	4.12
Coefficient of variation (CV %)					30.605	46.04
Normality test (Anderson-Darling Test): p-value					0.013	

Table A-15: Results of Testing Input Yarn 16 for Bending Using the Initial Bending Frame

Input yarn 16	**Stiff acrylic, 140 tex, colour: beige**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	100	0.013	45	3.5	18.098	3.64
2	100	0.013	43	3.5	17.452	3.51
3	100	0.014	70	4.5	15.244	8.53
4	110	0.015	59	4	26.73	4.48
5	110	0.015	57	3	35.222	3.24
6	110	0.015	64	7.5	14.416	9.26
7	115	0.016	59	6.5	19.732	6.62
8	115	0.016	63	6	21.835	6.58
9	115	0.013	62	6	17.672	3.81
10	120	0.016	62	6.5	22.485	6.39
11	120	0.016	65	11.5	12.909	11.81
12	120	0.016	68	9.5	15.748	10.35
13	125	0.017	79	5	35.302	6.20
14	125	0.017	75	8	22.412	9.09
15	125	0.017	78	12.5	14.194	14.89
				Average	20.630	7.41
				Standard deviation (SD)	7.031	3.29
				Coefficient of variation (CV %)	34.080	44.43
				Normality test (Anderson-Darling Test): p-value	0.028	

Table A-16: Results of Testing Input Yarn 17 for Bending Using the Initial Bending Frame

Input yarn 17	**Soft Shetland wool, R220/2 tex, colour: Lt. Camel**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	70	0.019	38	4	8.753	7.13
2	70	0.019	42	3	11.73	6.12
3	70	0.019	39	5	7.038	9.16
4	75	0.02	42	4	11.399	6.91
5	75	0.02	42	4	11.399	6.91
6	75	0.02	37	7.5	5.818	11.16
7	80	0.021	40	7	8	9.93
8	80	0.021	48	6.5	8.932	11.48
9	80	0.021	45	9	6.459	14.42
10	85	0.023	46	5	15.165	7.31
11	85	0.023	48	7.5	10.187	11.46
12	85	0.023	49	7	10.928	11.00
13	75	0.019	46	6	7.17	11.69
14	75	0.019	39	3.5	12.137	5.55
15	75	0.019	45	7.5	5.771	14.04
				Average	9.392	9.62
				Standard deviation (SD)	2.737	2.85
				Coefficient of variation (CV %)	29.144	29.59
				Normality test (Anderson-Darling Test): p-value	0.505	

Table A-17: Results of Testing Input Yarn 18 for Bending Using the Initial Bending Frame

Input yarn 18	**Lambswool/Cashmere, R120/2 tex, colour: Lt. Camel**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	55	0.006	33	2	2.695	5.19
2	55	0.006	33	2	2.695	5.19
3	55	0.006	30	1	5.369	2.29
4	60	0.007	31	3	2.664	5.91
5	60	0.007	36	3	2.721	7.13
6	60	0.007	25	2	3.455	3.27
7	65	0.007	42	5	2.02	12.26
8	65	0.007	40	2.5	4.128	5.71
9	65	0.007	43	4	2.486	10.30
10	65	0.007	37	4	2.601	8.13
11	70	0.008	39	4	3.704	7.35
12	70	0.008	47	5.5	2.551	13.45
13	70	0.008	42	4	3.704	8.13
14	70	0.008	43	5.5	2.679	11.51
15	75	0.009	55	5	3.478	14.04
Average					3.183	8.25
Standard deviation (SD)					0.811	3.46
Coefficient of variation (CV %)					25.487	42.00
Normality test (Anderson-Darling Test): p-value					0.030	

Table A-18: Results of Testing Input Yarn 19 for Bending Using the Initial Bending Frame

Input yarn 19	**Wool/Linen/Cotton, R180/2 tex, Colour: Purity**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	60	0.012	34	2.5	5.61	5.49
2	60	0.012	39	3	4.524	8.13
3	60	0.012	41	1	13.041	3.01
4	60	0.012	35	1.5	9.357	3.43
5	70	0.14	46	3	8.323	7.13
6	70	0.14	48	2.5	9.63	6.48
7	70	0.14	35	3	8.337	4.90
8	70	0.14	32	3	7.89	4.51
9	80	0.04	46	4.5	8.626	7.54
10	80	0.04	44	6	6.437	9.46
11	80	0.04	44	2.5	15.449	3.97
12	80	0.017	44	4	11.725	6.34
13	90	0.017	52	6	11.187	8.97
14	90	0.017	55	9	7.406	14.42
15	90	0.017	39	6	9.768	6.71
Average					9.154	6.70
Standard deviation (SD)					2.851	2.89
Coefficient of variation (CV %)					31.145	43.09
Normality test (Anderson-Darling Test): p-value					0.819	

Table A-19: Results of Testing Input Yarn 20 for Bending Using the Initial Bending Frame

Input yarn 20	**Bleached Cotton, R295/5 tex**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	65	0.020	37	1.5	19.821	3.07
2	65	0.020	37	2.5	11.892	5.10
3	65	0.020	35	1.5	19.631	2.86
4	70	0.021	45	2	18.984	4.57
5	70	0.021	38	2	19.396	3.58
6	70	0.021	43	2	19.345	4.24
7	75	0.022	46	6	8.312	11.69
8	75	0.022	45	5	10.023	9.46
9	75	0.022	37	4	12.001	6.01
10	80	0.024	47	6	11.086	10.30
11	80	0.024	41	3	21.579	4.40
12	80	0.024	45	5	13.289	8.13
13	85	0.025	42	3.5	22.707	4.65
14	85	0.025	55	5	16.125	9.46
15	85	0.025	49	7	11.878	11.00
16	65	0.02	37	1.5	19.821	3.07
				Average	15.738	6.57
				Standard deviation (SD)	4.711	3.10
				Coefficient of variation (CV %)	29.933	47.14
				Normality test (Anderson-Darling Test): p-value	0.063	

Table A-20: Results of Testing Input Yarn 21 for Bending Using the Initial Bending Frame

Input yarn 21	**Cotton, Undyed, R144/2 tex**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	60	0.0095	30	4	2.671	7.59
2	60	0.0083	35	4	2.427	9.09
3	60	0.0078	34	5	1.823	10.89
4	55	0.007	33	3	2.096	7.77
5	55	0.007	33	4	1.572	10.30
6	55	0.0074	29	3	2.186	6.58
7	55	0.0073	27	3	2.088	6.12
8	55	0.0069	31	2	3.104	4.76
9	55	0.0063	36	2.5	2.185	7.50
10	50	0.0064	32	2	2.113	6.34
11	50	0.0066	34	2	2.085	7.13
12	50	0.0063	27	1.5	2.816	3.73
13	45	0.0053	29	1.5	1.694	5.36
14	45	0.0067	23	1	3.212	2.60
15	45	0.0061	27	2	1.5	6.34
				Average	2.238	6.81
				Standard deviation (SD)	0.521	2.25
				Coefficient of variation (CV %)	23.276	32.99
				Normality test (Anderson-Darling Test): p-value	0.293	

Table A-21: Results of Testing Input Yarn 22 for Bending Using the Initial Bending Frame

Input yarn 22	**Bamboo Ne 24/3**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	40	0.0033	20.5	2.5	0.445	7.31
2	40	0.003	22.5	1	1.038	3.27
3	40	0.0034	19	1.5	0.733	4.09
4	45	0.0035	25	1	1.721	2.86
5	45	0.0037	25	1.5	1.213	4.29
6	45	0.0034	23	1	1.630	2.60
7	50	0.0039	21	1	2.244	1.97
8	50	0.0043	30	4	0.725	11.31
9	50	0.0034	28	1.5	1.531	3.90
10	55	0.0048	24	3.25	1.168	5.98
11	55	0.0044	29.5	2.5	1.568	5.60
12	55	0.0044	33	4.23	0.930	10.88
13	60	0.005	32	5	1.201	10.12
14	60	0.005	32	5.25	1.077	10.62
15	60	0.005	34	2.5	2.197	5.49
Average					1.295	6.02
Standard deviation (SD)					0.520	3.26
Coefficient of variation (CV %)					40.132	54.11
Normality test (Anderson-Darling Test): p-value					0.653	

Table A-22: Results of Testing Input Yarn 23 for Bending Using the Initial Bending Frame

Input yarn 23	**Wool (quality: wind) 67 tex Colour: Camel**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	50	0.0047	32.5	2.75	1.118	8.93
2	50	0.0041	32	3.5	0.773	11.00
3	50	0.0042	20	2.75	0.84	5.24
4	55	0.0039	24.5	3	1.045	5.62
5	55	0.0033	35	3	0.969	8.53
6	55	0.0049	35.5	3	1.429	8.75
7	60	0.0042	36	5.5	0.89	12.91
8	60	0.0044	35	3.75	1.372	8.53
9	60	0.0041	38	4	1.175	10.30
10	60	0.0041	38	4	1.175	10.30
11	65	0.005	36	5.5	1.346	10.74
12	65	0.0048	42.5	4	1.719	10.08
13	65	0.0049	29	5.75	1.132	9.07
14	65	0.005	35	6.25	1.107	11.77
15	65	0.005	34	4.5	1.62	8.26
Average					1.181	9.27
Standard deviation (SD)					0.284	2.12
Coefficient of variation (CV %)					24.064	22.89
Normality test (Anderson-Darling Test): p-value					0.710	

Table A-23: Results of Testing Input Yarn 24 for Bending Using the Initial Bending Frame

Input yarn 24	**Wool /Angora /Polyamide (60/20/20) 67 tex**					
Specimen	**L** (mm)	**W** (g)	$\boldsymbol{x}$ (mm)	$\boldsymbol{y}$ (mm)	**B** (g mm^2)	$\boldsymbol{\theta = \arctan(\frac{y}{L-x})}$
1	55	0.0046	33	2.5	1.653	6.48
2	55	0.0036	31	2.5	1.295	5.94
3	55	0.0042	29.5	1.75	2.138	3.92
4	55	0.004	31.5	2.25	1.601	5.46
5	55	0.004	36.5	2.25	1.526	6.93
6	60	0.0042	38	2.5	1.927	6.48
7	60	0.004	35	2	2.339	4.57
8	60	0.0037	39	2.25	1.86	6.11
9	60	0.0041	37.5	3	1.576	7.59
10	60	0.0041	37.5	3	1.576	7.59
11	65	0.0047	32.5	3.5	1.92	6.14
12	65	0.004	31	4.25	1.31	7.12
13	65	0.0046	37	4.5	1.519	9.13
14	65	0.0048	40	5	1.415	11.30
15	65	0.0041	42.5	4.25	1.382	10.69
				Average	1.675786	6.99
				Standard deviation (SD)	0.317003	2.11
				Coefficient of variation (CV %)	18.91668	30.19
				Normality test (Anderson-Darling Test): p-value	0.308	

Table A-24: Results of Testing Input Yarn 25 for Bending Using the Initial Bending Frame

Input yarn 25	**Wool , R118/2 tex, Colour: DK Green**					
Specimen	**L** (mm)	**W** (g)	x (mm)	y (mm)	**B** (g mm^2)	$\theta = \arctan(\frac{y}{L-x})$
1	60	0.0071	28	2	3.831	3.58
2	60	0.0086	30	3	2.55	5.71
3	60	0.0071	36	3	2.76	7.13
4	65	0.0069	21.5	2	3.38	2.63
5	65	0.0085	42	3	4.09	7.43
6	65	0.0085	42	3	4.09	7.43
7	70	0.0095	37	2.5	6.948	4.33
8	70	0.009	42	3.5	4.762	7.13
9	70	0.0087	43	4	4.007	8.43
10	75	0.01	45	6.5	3.504	12.23
11	75	0.0089	48	3.5	5.668	7.39
12	75	0.0093	38	4.5	4.57	6.93
13	80	0.0105	46	7	4.16	11.63
14	75	0.0092	43	5.5	3.821	9.75
15	75	0.0094	41	4.5	4.742	7.54
Average					4.20	6.85
Standard deviation (SD)					1.13	3.11
Coefficient of variation (CV %)					27.02	45.36
Normality test (Anderson-Darling Test): p-value					0.356	

A-2: The Results Testing a Rubber String Using the Initial Bending Frame

Table A-25: The Results of Testing a String of Rubber Using the Initial Bending Frame

specimen	***L* (mm)**	***x* (mm)**	***y* values having " –" sign (mm)**	**W (g)**	**B: Bending stiffness of thread (g mm^2)**	**comments**
1	40	17	2	0.0214	3.185	*
2	40	21	1.5	0.0214	4.856	*
3	40	27.5	5	0.0214	3.424	*
3	40	31	1	0.0214	5.591	Swapping the ends of the specimen
4	45	27	3.5	0.0230	3.233	*
4	45	21	1.5	0.0230	6.987	Swapping the ends of the specimen
4	45	20	1.75	0.0230	5.780	Releasing the free end of specimen then return it back to the testing frame.
5	50	29	3.25	0.0267	5.561	*
5	50	30	3.50	0.0267	5.149	Releasing the free end of specimen then returning it back
5	50	22	1.5	0.0267	10.654	Swapping the two ends of the specimen
5	50	28	2.5	0.0267	7.215	Releasing the specimen, turning it then returning it back
				Average	5.603	*
				SD	2.169	*
				CV%	38.7	*

A-3: The Results of Testing a Sewing Thread Using the Initial Bending Frame

Table A-26: Testing the Sewing Thread Using the Initial Bending Frame

specimen	***L* (mm)**	***x* (mm)**	***y* values having " –" sign (mm)**	**W (g)**	**B: Bending stiffness of thread (g mm^2)**	**comments**
1	60	22.5	1	0.0042	3.738	
1	60	39	1.25	0.0042	3.801	Releasing the free end of specimen and re-fixing it
1	60	22	0.75	0.0042	4.864	Releasing the specimen and swapping the two ends
				Average of specimen 1	4.134	
				SD of specimen 1	0.633	
				CV of Specimen 1	15.30	
2	60	11.5	0.5	0.0050	3.497	
2	60	31.5	1.25	0.0050	4.595	Releasing the free end of specimen and turn it.
2	60	30	0.75	0.0050	7.5	Releasing the specimen and swapping its ends
				Average of specimen 2	5.197	
				SD of specimen 2	2.069	
				CV of specimen 2	39.80	
3	60	28	0.75	0.0043	6.193	
3	60	37	0.75	0.0043	6.644	Releasing the free end of specimen, turning it and returning it back to the testing frame.
3	60	31	1	0.0043	4.91	Releasing the specimen and swapping its ends
				Average of specimen 3	5.916	
				SD of specimen 3	0.81	
				CV of specimen 3	15.21	
Grand average (average of averages)		5.082	**Average of all individual measurements**		5.082	
SD of the averages [25]		0.896	**SD of all individual measurements**		1.402	
CV of the averages		17.64	**CV% of all individual measurements**		27.64	

[25] This value was useful for comparison with the results of the Kawabata's Pure Bending Tester KES-FB-2.

A-4: The Results of Testing the Input Yarns Using the Kawabata' Pure Bending Tester KES-FB-2

Table A-27: Results of Testing the Input Yarns for Bending Using the Kawabata's Pure bending Tester

Sample Number	Yarn type	Colour	Resultant Linear Density tex	Kawabata's Measurements g mm^2
1	Pure wool, Glenshear	Fawn	R 120/2	1.8
2	Stiff acrylic, core yarn	Beige	140	6.5
3	Acrylic R72/2	Canary, cerise	R 72/2	0.7
4	Cotton/lambswool	undyed	R 120/2	1.75
5	Cotton, (Andy's cotton)	Lt. Camel	R 72/3	0.7
6	Stiff acrylic, effect yarn	Beige	140	Not measured
7	Combed cotton	Amber	R 126/3	1
8	Soft Shetland wool	Lt. Camel	R 220/2	Not measured
9	Natural wool	Natural	R 195/2	3
10	Lambswool	Honeysuckle	R 120/2	1.7
11	Wool/polyamide	Aroma	R 120/2	2.4
12	Lambswool/viscose, 60/40	Gretna Green	R 120/2	1.3
13	Lambswool/Cashmere,	Lt. Camel	R 120/2	1.2
14	Wool/Linen/Cotton	Purity	R 180/2	2.4
15	Wool/Cotton, 50/50	Snapdragon	R 163/2	Not measured
16	Cotton	Bleached	R 295/5	Not measured
17	Wool/Nylon	Camel	R 120/2	1.65
18	Linen/Cotton	SAND	R 144/2	1.6

A-5: The Results of Testing a Sewing Thread Using the Improved Bending Frame

Table A-28: Results of Testing the Ne=2/2/3 Core-spun Sewing Thread Using the Improve Bending Frame

specimen	*L* (mm)	*x* (mm)	*y* values having "–" sign (mm)	W (g)	B: Bending stiffness of thread (g mm^2)
1	50	21	1.25	0.0048	2.21
2	50	17	1	0.0049	2.258
3	50	22	1	0.0048	2.873
				average of 50 mm specimens	2.447
				SD of 50 mm specimens	0.370
				CV% of 50 mm specimens	15.11
4	55	19.5	1	0.0045	2.899
5	55	22	1	0.0052	3.807
6	55	26	0.75	0.005	5.594
				average of 55 mm specimens	4.100
				SD of 55 mm specimens	1.371
				CV% of 55 mm specimens	33.44
7	60	33	1.25	0.0053	4.935
8	60	28	1	0.0053	5.725
9	60	29.5	0.75	0.005	7.434
				average of 60 mm specimens	6.031
				SD of 60 mm specimens	1.277
				CV% of 60 mm specimens	21.18
10	65	32	1	0.0055	7.803
11	65	29	1	0.0049	6.514
12	65	17	1	0.006	4.295
				average of 65 mm specimens	6.204
				SD of 65 mm specimens	1.774
				CV% of 65 mm specimens	28.60
13	70	29	1	0.0057	8.891
14	70	35	1.25	0.0062	8.861
15	70	38	3.25	0.0064	3.629
				average of 70 mm specimens	7.127
				SD of 70 mm specimens	3.029
Grand average		5.182		**CV% of 70 mm specimens**	42.51
Average of SDs		1.564		**Average of all individual measurements**	5.182
SD of the averages		1.884		**SD of all individual measurements**	2.308
CV of the averages		36.36		**CV% of all individual measurements**	44.532

A-6: The Results of Testing a Sewing Thread Using the Ring-Loop Method

Table A-29: Results of Measurements of Bending Stiffness of an Ne=2/2/3 Sewing Thread Using the Ring Method

Specimen	$2\pi r$ (mm)	H_1 (mm)	H_2 (mm)	$d=H_2-H_1$ (mm)	θ	$\cos\theta$	$\tan\theta$	B: Bending stiffness of thread (g mm^2)
1	60	18	19	1	8.217	0.990	0.144	4.117
2	60	19.5	20	0.5	4.108	0.997	0.072	8.341
3	60	18.5	19	0.5	4.108	0.997	0.072	8.341
	Average of 60 mm specimens							6.933
	SD of 60 mm specimens							2.439
	CV% of 60 mm specimens							35.18
4	65	20	21	1	7.585	0.991	0.133	5.248
5	65	20.5	21	0.5	3.792	0.998	0.066	10.612
6	65	20	20.5	0.5	3.792	0.998	0.066	10.612
	average of 65 mm specimens							8.824
	SD of 65 mm specimens							3.097
	CV% of 65 mm specimens							35.10
7	70	21.75	22.75	1	7.043	0.992	0.124	6.568
8	70	22.5	23.5	1	7.043	0.992	0.124	6.568
9	70	22	23	1	7.043	0.992	0.124	6.568
	Average of 70 mm specimens							6.568
	SD of 70 mm specimens							0.000
	CV% of 70 mm specimens							0.00
10	75	23.75	25.5	1.75	11.503	0.980	0.204	4.519
11	75	24.75	26	1.25	8.217	0.990	0.144	6.433
12	75	24.5	25.5	1	6.573	0.993	0.115	8.091
	average of 75 mm specimens							6.348
	SD of 75 mm specimens							1.788
	CV% of 75 mm specimens							28.16
13	80	26.5	28	1.5	9.244	0.987	0.163	6.476
14	80	25.5	27	1.5	9.244	0.987	0.163	6.476
15	80	25.75	27.5	1.75	10.784	0.982	0.190	5.507
	average of 80 mm specimens							6.153
	SD of 80 mm specimens							0.559
Grand average		6.965		**CV% of 80 mm specimens**				9.09
Average of SDs		1.577		**Average of all individual measurements**				6.965
SD of the averages		1.079		**SD of all individual measurements**				1.928
CV of the averages		15.49		**CV% of all individual measurements**				27.685

A-7: Data of the $\overline{x}$-SD Control Chart

Table A-30: The Results of Testing the Second Group of Plastic Strips at a Constant length

specimen	subgroup	Bending stiffness g mm^2	Linear density tex	Specific bending stiffness g $mm^2 tex^{-2} 1000^{-1}$	specimen	subgroup	Bending stiffness g mm^2	Linear density tex	Specific bending stiffness g $mm^2 tex^{-2} 1000^{-1}$
1	1	177.07	639.00	433.66	36	8	181.87	631.00	456.79
2		148.77	603.00	409.14	37		156.24	641.00	380.26
3		147.73	610.00	397.02	38		171.30	706.00	343.68
4		158.45	636.00	391.71	39		151.26	623.00	389.71
5		170.77	615.00	451.51	40		190.46	667.00	428.10
6	2	161.97	640.00	395.43	41	9	174.70	641.00	425.17
7		191.44	678.00	416.46	42		184.40	630.00	464.59
8		176.22	628.00	446.81	43		184.02	641.00	447.87
9		179.10	664.00	406.22	44		151.52	626.00	386.64
10		187.53	636.00	463.62	45		171.70	646.00	411.44
11	3	155.93	648.00	371.33	46	10	162.07	626.00	413.58
12		158.36	595.00	447.32	47		173.56	633.00	433.15
13		153.36	626.00	391.36	48		160.00	646.00	383.41
14		159.11	640.00	388.46	49		167.90	641.00	408.64
15		166.12	678.00	361.38	50		165.41	606.00	450.41
16	4	159.59	635.00	395.78	51	11	151.04	625.00	386.67
17		155.65	625.00	398.46	52		169.62	635.00	420.65
18		184.03	648.00	438.28	53		194.61	658.00	449.47
19		162.85	646.00	390.24	54		170.21	660.00	390.75
20		174.18	623.00	448.78	55		185.15	649.00	439.58
21	5	156.78	636.00	387.59	56	12	175.91	674.00	387.23
22		161.54	638.00	396.86	57		161.73	632.00	404.90
23		155.12	639.00	379.88	58		185.97	622.00	480.68
24		196.23	683.00	420.65	59		170.91	644.00	412.09
25		168.89	683.00	362.04	60		164.07	640.00	400.55
26	6	157.20	625.00	402.43	61	13	171.74	641.00	417.98
27		155.77	655.00	363.07	62		171.67	640.00	419.12
28		181.78	675.00	398.97	63		168.02	657.00	389.26
29		177.86	633.00	443.87	64		185.18	664.00	420.02
30		178.33	645.00	428.65	65		179.67	604.00	492.50
31	7	151.16	627.00	384.49	66	14	176.60	636.00	436.60
32		165.11	657.00	382.51	67		170.93	648.00	407.07
33		150.56	633.00	375.74	68		191.47	648.00	455.98
34		170.56	666.00	384.54	69		156.38	614.00	414.80
35		154.71	631.00	388.56	70		186.81	632.00	467.70

A-8: The Results of Measuring the Impact of Specimen Length on Variability of Bending Stiffness

Table A-31: The Results of Testing the Second Group of Plastic Strips at Variable Specimen lengths

specimen	Length of specimen mm	Bending stiffness g mm^2	Linear density tex	Specific bending stiffness g mm^2 tex^{-2} 1000^{-1}
1	90	147.85	618.89	238.89
2	90	159.81	613.33	260.56
3	90	154.87	644.44	240.31
4	90	154.23	650.00	237.28
5	90	160.52	608.89	263.63
6	95	188.38	658.95	285.88
7	95	160.38	660.00	243.00
8	95	166.60	618.95	269.17
9	95	192.62	652.63	295.15
10	95	152.23	644.21	236.30
11	105	189.43	636.19	297.76
12	105	181.01	630.48	287.10
13	105	213.82	647.62	330.16
14	105	211.29	641.90	329.16
15	105	227.76	660.95	344.59
16	110	196.83	635.45	309.74
17	110	196.57	637.27	308.46
18	110	202.81	660.00	307.28
19	110	198.58	645.45	307.66
20	110	193.82	637.27	304.14
average		182.47	640.14	284.81
SD		23.70	15.72	34.18
CV %		12.99	2.46	12.00

A-9: The Results of Using the Improved Bending Frame and the Digital Image Analysis

Table A-32: Results of Testing Input Yarn 1 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number: 1		**Soft acrylic, R72/2 tex (colour: canary, cerise),**										**Test length =50 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B ($g\ mm^2$)**
1	740	3822	266	2352	74	51.65	3.595	31.784	0.97	3.480	30.769	0.0033	0.636
2	752	3842	215	2006	75.2	51.09	2.859	26.676	0.98	2.798	26.106	0.0034	0.806
3	751	3842	303	2608	75.1	51.16	4.035	34.727	0.98	3.943	33.941	0.0038	0.61
4	537	2737	177	1289	53.7	50.97	3.296	24.004	0.98	3.233	23.548	0.004	0.778
5	521	2676	158	1322	52.1	51.36	3.033	25.374	0.97	2.952	24.701	0.0036	0.789
6	527	2697	332	1686	52.7	51.18	6.300	31.992	0.98	6.155	31.257	0.0035	0.379
7	526	2725	300	1489	52.6	51.81	5.703	28.308	0.97	5.505	27.321	0.0037	0.452
8	527	2748	217	1338	52.7	52.14	4.118	25.389	0.96	3.948	24.345	0.0035	0.569
9	526	2748	194	1320	52.6	52.24	3.688	25.095	0.96	3.530	24.017	0.0038	0.686
10	526	2739	221	1214	52.6	52.07	4.202	23.080	0.96	4.034	22.161	0.0036	0.537
11	527	2744	186	1170	52.7	52.07	3.529	22.201	0.96	3.389	21.319	0.0033	0.568
12	524	2733	152	1499	52.4	52.16	2.901	28.607	0.96	2.781	27.424	0.0036	0.871
13	525	2749	119	1324	52.5	52.36	2.267	25.219	0.95	2.164	24.081	0.0032	0.943
14	525	2735	205	1256	52.5	52.10	3.905	23.924	0.96	3.748	22.962	0.0031	0.511
15	523	2729	148	1186	52.3	52.18	2.830	22.677	0.96	2.712	21.730	0.0033	0.526
16	523	2738	233	1478	52.3	52.35	4.455	28.260	0.96	4.255	26.991	0.0037	0.583
17	523	2717	197	1339	52.3	51.95	3.767	25.602	0.96	3.625	24.641	0.0033	0.588
18	512	2670	217	1368	51.2	52.15	4.238	26.719	0.96	4.064	25.618	0.0039	0.632
19	513	2657	185	1460	51.3	51.79	3.606	28.460	0.97	3.481	27.475	0.0032	0.619
20	513	2658	133	1565	51.3	51.81	2.593	30.507	0.97	2.502	29.439	0.0034	0.919
												average	0.650
												standard deviation	0.154
												CV%	23.757

Table A-33: Results of Testing Input Yarn 2 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 2		Lambswool/cotton, R120/2 tex, (colour: natural),										Test length=65 mm	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	629	4000	305	2391	62.9	63.59	4.849	38.013	1.02	4.956	38.854	0.0069	2.066
2	630	3998	270	2380	63	63.46	4.286	37.778	1.02	4.390	38.694	0.0073	2.469
3	631	3993	111	2064	63.1	63.28	1.759	32.710	1.03	1.807	33.599	0.0071	5.705
4	630	3992	131	1927	63	63.37	2.079	30.587	1.03	2.133	31.377	0.0075	4.934
5	629	3993	243	2048	62.9	63.48	3.863	30.636	1.02	3.956	31.369	0.0075	2.660
6	632	3998	84	2364	63.2	63.26	1.329	32.405	1.03	1.366	33.297	0.0078	8.260
7	629	4008	101	2220	62.9	63.72	1.606	37.583	1.02	1.638	38.338	0.008	7.258
8	634	4015	336	2483	63.4	63.33	5.300	39.164	1.03	5.440	40.198	0.0075	2.030
9	635	4012	196	2192	63.5	63.18	3.087	34.520	1.03	3.175	35.513	0.0086	4.003
10	635	4027	226	2071	63.5	63.42	3.559	32.614	1.02	3.648	33.428	0.0078	3.098
11	635	4033	146	2083	63.5	63.51	2.299	32.803	1.02	2.353	33.572	0.0075	4.627
12	635	4023	152	2185	63.5	63.51	2.394	34.409	1.02	2.450	35.216	0.0077	4.635
13	633	4021	174	2347	63.3	63.55	2.749	37.077	1.02	2.811	37.921	0.0073	3.862
14	635	4019	280	2129	63.5	63.32	4.409	33.528	1.03	4.526	34.416	0.0069	2.233
15	632	3998	278	2456	63.2	63.59	4.399	38.861	1.02	4.496	39.721	0.0076	2.497
16	633	4002	187	1978	63.3	63.16	2.954	31.248	1.03	3.040	32.159	0.0068	3.182
17	632	4001	276	2352	63.2	63.32	4.367	37.215	1.03	4.483	38.201	0.007	2.321
18	633	4007	282	2098	63.3	63.21	4.455	33.144	1.03	4.581	34.084	0.007	2.231
19	633	3997	259	2325	63.3	63.30	4.092	36.730	1.03	4.201	37.715	0.0081	2.868
20	632	4011	289	2426	63.2	63.24	4.573	38.386	1.03	4.700	39.452	0.0073	2.298
												average	3.662
												standard deviation	1.774
												CV%	48.46

Table A-34: Results of Testing Input Yarn 3 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 3	**Combed cotton, R126/3 tex, (colour: amber),**										**Test length= 50 mm**		
specimen	**10 mm = pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	686	3379	276	1985	68.6	49.26	4.023	28.936	1.02	4.084	29.373	0.0063	1.044
2	384	3375	92	1738	38.4	87.89	2.396	45.260	0.57	1.363	25.748	0.0056	2.711
3	485	2388	118	1380	48.5	49.24	2.433	28.454	1.02	2.471	28.894	0.0065	1.781
4	486	2393	139	1345	48.6	49.24	2.860	27.675	1.02	2.904	28.103	0.0058	1.350
5	486	2395	117	1337	48.6	49.28	2.407	27.675	1.01	2.443	28.079	0.0058	1.604
6	486	2402	195	1188	48.6	49.42	4.012	27.510	1.01	4.059	27.831	0.0057	0.948
7	486	2400	193	1380	48.6	49.38	3.971	24.444	1.01	4.021	24.750	0.0059	0.950
8	486	2400	180	1461	48.6	49.38	3.704	30.062	1.01	3.750	30.438	0.0064	1.149
9	486	2404	123	1168	48.6	49.47	2.531	24.033	1.01	2.558	24.293	0.0061	1.529
10	488	2391	139	1248	48.8	49.00	2.848	25.574	1.02	2.907	26.098	0.0065	1.483
11	488	2384	103	1214	48.8	48.85	2.111	24.877	1.02	2.160	25.461	0.0063	1.915
12	486	2395	129	1317	48.6	49.05	2.654	27.099	1.02	2.706	27.622	0.0063	1.569
13	487	2408	176	1528	48.7	49.18	3.614	31.376	1.02	3.674	31.900	0.0061	1.098
14	487	2408	40	969	48.7	49.45	0.821	19.897	1.01	0.831	20.120	0.0064	4.260
15	488	2394	149	1446	48.8	49.34	3.053	29.631	1.01	3.094	30.025	0.0061	1.331
16	488	2410	167	1366	48.8	49.06	3.422	27.992	1.02	3.488	28.530	0.0063	1.222
17	488	2407	111	1465	48.8	49.39	2.275	30.020	1.01	2.303	30.394	0.0064	1.871
18	489	2412	141	1275	48.9	49.22	2.883	26.074	1.02	2.929	26.485	0.0062	1.412
19	690	3398	230	1918	69	34.96	3.333	27.797	1.43	4.768	39.760	0.0065	0.648
20	688	3399	153	1600	68.8	49.39	2.224	23.256	1.01	2.251	23.543	0.0061	1.704
												average	1.579
												standard deviation	0.774
												CV%	48.99

Table A-35: Results of Testing Input Yarn 4 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 4		**Natural wool, R195/2 tex, , (colour: Natural),**										**Test length=75 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	520	3757	362	2390	52	72.25	6.962	45.962	1.04	7.227	47.711	0.0135	4.177
2	520	3764	165	2398	52	72.38	3.173	46.115	1.04	3.288	47.782	0.0145	9.853
3	520	3730	391	2501	52	71.73	7.519	48.096	1.05	7.862	50.288	0.0147	4.038
4	519	3769	327	2407	51.9	72.62	6.301	46.378	1.03	6.507	47.897	0.014	4.801
5	522	3763	272	2403	52.2	72.09	5.211	46.034	1.04	5.421	47.894	0.014	5.763
6	522	3759	295	1932	52.2	72.01	5.651	37.011	1.04	5.886	38.547	0.0143	5.406
7	520	3757	308	2010	52	72.25	5.923	38.654	1.04	6.149	40.125	0.0144	5.287
8	520	3768	212	1344	52	72.46	4.077	25.846	1.04	4.220	26.752	0.0129	5.028
9	521	3781	232	1987	52.1	72.57	4.453	38.138	1.03	4.602	39.414	0.0145	7.072
10	520	3742	383	2575	52	71.96	7.365	49.519	1.04	7.676	51.610	0.0145	3.981
11	520	3753	452	2053	52	72.17	8.692	39.481	1.04	9.033	41.027	0.0135	3.393
12	521	3741	372	2285	52.1	72.03	7.140	43.858	1.04	7.434	45.663	0.0137	4.186
13	520	3751	317	2402	52	71.94	6.096	46.192	1.04	6.355	48.156	0.0145	5.077
14	519	3775	160	1479	51.9	72.27	3.083	28.497	1.04	3.199	29.572	0.0148	8.468
15	519	3757	320	2142	51.9	72.74	6.166	41.272	1.03	6.358	42.556	0.0147	5.279
16	517	3760	322	2223	51.7	72.67	6.228	42.998	1.03	6.428	44.377	0.0142	5.042
17	518	3749	256	2640	51.8	72.59	4.942	50.965	1.03	5.106	52.660	0.0145	5.849
18	518	3748	390	2085	51.8	72.37	7.529	40.251	1.04	7.802	41.711	0.0135	3.941
19	517	3748	344	1712	51.7	72.50	6.654	33.114	1.03	6.884	34.258	0.0139	4.197
20	516	3731	388	2045	51.6	72.64	7.519	39.632	1.03	7.764	40.922	0.0142	4.15
												average	5.249
												standard deviation	1.601
												CV%	30.492

Table A-36: Results of Testing Input Yarn 5 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 5		Lambswool, R120/2 tex, (colour: honeysuckle),										Test length= 60 mm	
specimen	10 mm = in pixel	L (pixel)	y (pixel)	x (pixel)	1 mm= in pixel	L (mm)	y (mm)	x (mm)	L set /L measured	y corrected	x corrected	W (g)	B (g mm^2)
1	673	3950	206	2036	67.3	58.69	3.061	30.253	1.02	3.129	30.927	0.0079	2.880
2	673	3970	190	1390	67.3	58.99	2.823	20.654	1.02	2.872	21.008	0.0079	2.268
3	679	3971	354	1791	67.9	58.48	5.214	26.377	1.03	5.349	27.061	0.0075	1.478
4	674	3950	264	1964	67.4	58.61	3.917	29.139	1.02	4.010	29.833	0.0073	2.042
5	677	3957	191	2233	67.7	58.45	2.821	29.010	1.03	2.896	29.780	0.0068	2.632
6	678	3952	323	1927	67.8	58.29	4.764	32.935	1.03	4.904	33.902	0.0069	1.644
7	670	3952	195	2176	67	58.99	2.910	28.761	1.02	2.961	29.256	0.0073	2.737
8	676	3951	325	2307	67.6	58.45	4.808	34.127	1.03	4.935	35.034	0.0085	2.015
9	673	3944	278	2027	67.3	58.60	4.131	30.119	1.02	4.229	30.837	0.0067	1.805
10	669	3919	113	2042	66.9	58.58	1.689	30.523	1.02	1.730	31.263	0.0072	4.768
11	672	3920	210	2427	67.2	58.33	3.125	36.116	1.03	3.214	37.148	0.0074	2.665
12	672	3924	136	2049	67.2	58.33	2.024	30.491	1.03	2.082	31.362	0.0056	3.085
13	672	3921	120	2538	67.2	58.39	1.786	37.768	1.03	1.835	38.807	0.0076	4.699
14	674	3927	209	1695	67.4	58.18	3.101	25.148	1.03	3.198	25.937	0.0066	2.104
15	668	3925	227	2267	66.8	58.79	3.398	33.937	1.02	3.468	34.637	0.0069	3.328
16	673	3929	364	2175	67.3	58.32	5.409	32.318	1.03	5.564	33.248	0.0064	1.341
17	666	3935	189	2068	66.6	58.99	2.838	31.051	1.02	2.886	31.581	0.0085	3.387
18	666	3932	252	2175	66.6	59.08	3.784	32.658	1.02	3.842	33.164	0.0065	1.971
19	672	3935	268	2360	67.2	58.51	3.988	35.119	1.03	4.090	36.012	0.0066	1.882
20	676	3925	292	2253	67.6	58.21	4.320	33.328	1.03	4.452	34.353	0.0062	1.629
												average	2.518
												standard deviation	0.966
												CV%	38.34

Table A-37: Results of Testing Input Yarn 6 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 6		**Wool/polyamide, R120/2 tex, (colour: Aroma),**										**Test length=60 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	670	3909	110	1830	67	58.34	1.642	27.313	1.03	1.688	28.089	0.0072	4.617
2	671	3909	144	1442	67.1	58.26	2.146	21.490	1.03	2.210	22.134	0.0087	7.884
3	669	3909	336	2331	66.9	58.43	5.022	34.843	1.03	5.157	35.779	0.0077	1.743
4	669	3904	83	1763	66.9	58.36	1.241	26.353	1.03	1.276	27.095	0.0085	7.030
5	670	3910	160	1586	67	58.36	2.388	26.313	1.03	2.455	27.054	0.008	3.435
6	670	3909	173	1477	67	58.34	2.582	23.672	1.03	2.655	24.344	0.0076	2.758
7	670	3907	249	2393	67	58.31	3.716	22.045	1.03	3.824	22.682	0.0078	1.831
8	671	3910	162	1842	67.1	58.27	2.414	27.452	1.03	2.486	28.266	0.0085	3.716
9	672	3910	338	2267	67.2	58.18	5.030	33.735	1.03	5.187	34.788	0.0075	1.692
10	668	3905	282	2220	66.8	58.46	4.222	33.234	1.03	4.333	34.110	0.0086	2.320
11	671	3911	235	2217	67.1	58.29	3.502	33.040	1.03	3.605	34.012	0.0078	2.529
12	671	3908	297	2078	67.1	58.29	4.426	30.969	1.03	4.556	31.879	0.0089	2.253
13	668	3909	233	1924	66.8	58.50	3.488	28.802	1.03	3.577	29.539	0.0096	2.559
14	668	3907	303	2395	66.8	58.52	4.536	35.853	1.03	4.651	36.761	0.008	1.997
15	671	3911	191	2197	67.1	58.23	2.846	32.742	1.03	2.933	33.739	0.007	2.787
16	670	3914	145	1661	67	58.37	2.164	24.791	1.03	2.224	25.482	0.0083	3.748
17	670	3912	150	1932	67	58.42	2.239	28.836	1.03	2.299	29.617	0.008	3.889
18	669	3901	306	2085	66.9	58.48	4.574	31.166	1.03	4.693	31.979	0.0077	1.894
19	671	3911	256	2672	67.1	58.14	3.815	39.821	1.03	3.937	41.097	0.0094	2.589
20	671	3909	278	2500	67.1	58.29	4.143	37.258	1.03	4.265	38.353	0.0089	2.383
												average	3.183
												standard deviation	1.671
												CV%	52.51

Table A-38: Results of Testing Input Yarn 7 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 7		Lambswool/Viscose, R120/2 tex (colour: Gretna Green)										Test length=65 mm	
specimen	10 mm = in pixel	L (pixel)	y (pixel)	x (pixel)	1 mm= in pixel	L (mm)	y (mm)	x (mm)	L set /L measured	y corrected	x corrected	W (g)	B (g mm^2)
1	616	3914	182	2056	61.6	63.54	2.955	33.377	1.02	3.022	34.144	0.0083	4.013
2	617	3928	130	1024	61.7	63.66	2.107	16.596	1.02	2.151	16.945	0.0077	2.551
3	618	3924	210	2066	61.8	63.50	3.398	33.430	1.02	3.479	34.223	0.0079	3.321
4	616	3912	206	2012	61.6	63.51	3.344	32.662	1.02	3.423	33.430	0.0076	3.217
5	617	3899	179	2301	61.7	63.19	2.901	37.293	1.03	2.984	38.360	0.0079	3.934
6	616	3896	147	2282	61.6	63.25	2.386	37.045	1.03	2.453	38.072	0.0087	5.274
7	617	3902	199	1900	61.7	63.24	3.225	30.794	1.03	3.315	31.650	0.0069	2.935
8	616	3925	142	2232	61.6	63.72	2.305	36.234	1.02	2.352	36.963	0.0072	4.55
9	617	3924	139	1768	61.7	63.60	2.253	28.655	1.02	2.302	29.286	0.0077	4.48
10	615	3925	226	2356	61.5	63.82	3.675	38.309	1.02	3.743	39.017	0.0076	3.011
11	617	3924	107	1350	61.7	63.60	1.734	21.880	1.02	1.772	22.362	0.0085	4.926
12	612	3879	264	2183	61.2	64.12	4.314	35.670	1.01	4.373	36.161	0.0072	2.441
13	611	3971	115	2790	61.1	63.49	1.882	45.663	1.02	1.927	46.752	0.0079	5.319
14	609	3886	120	2123	60.9	65.21	1.970	34.860	1.00	1.964	34.751	0.0073	5.461
15	608	3871	347	1846	60.8	63.91	5.707	30.362	1.02	5.804	30.878	0.0073	1.747
16	610	3876	156	2622	61	63.46	2.557	42.984	1.02	2.619	44.027	0.0082	4.363
17	611	3881	186	1974	61.1	63.44	3.044	32.308	1.02	3.119	33.104	0.0089	4.117
18	611	3888	206	2400	61.1	63.52	3.372	39.280	1.02	3.450	40.196	0.0083	3.542
19	611	3887	167	2195	61.1	63.63	2.733	35.925	1.02	2.792	36.696	0.0081	4.31
20	610	3883	74	800	61	63.72	1.213	13.115	1.02	1.237	13.378	0.0079	3.182
												average	3.835
												standard deviation	1.033
												CV%	26.928

Table A-39: Results of Testing Input Yarn 8 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 8		**Wool + Cotton, R163/2 tex, (colour: Snapdragon),**										**Test length=80 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	499	3836	164	1820	49.9	76.87	3.287	36.473	1.04	3.420	37.956	0.0122	9.233
2	498	3836	366	2169	49.8	77.03	7.349	43.554	1.04	7.633	45.235	0.0126	4.573
3	499	3857	90	1300	49.9	77.29	1.804	26.052	1.04	1.867	26.964	0.0139	13.911
4	499	3847	412	2356	49.9	77.09	8.257	47.214	1.04	8.568	48.994	0.0113	3.63
5	499	3860	168	1476	49.9	77.35	3.367	29.579	1.03	3.482	30.591	0.0137	8.472
6	500	3859	309	2449	50	77.18	6.180	48.980	1.04	6.406	50.770	0.0131	5.555
7	500	3860	343	2132	50	77.20	6.860	42.640	1.04	7.109	44.187	0.0149	5.787
8	501	3874	223	1731	50.1	77.33	4.451	34.551	1.03	4.605	35.746	0.0137	7.382
9	498	3824	152	1810	49.8	76.79	3.052	36.345	1.04	3.180	37.866	0.0134	10.89
10	525	4051	411	2236	52.5	77.16	7.829	42.590	1.04	8.117	44.157	0.0132	4.489
11	527	4071	256	1964	52.7	77.25	4.858	37.268	1.04	5.031	38.595	0.0152	7.9
12	527	4060	138	2454	52.7	77.04	2.619	46.565	1.04	2.719	48.355	0.0117	11.881
13	526	4074	81	2374	52.6	77.45	1.540	45.133	1.03	1.591	46.618	0.0127	22.133
14	527	4060	349	2000	52.7	77.04	6.622	37.951	1.04	6.877	39.409	0.0123	4.733
15	528	4068	460	2300	52.8	77.05	8.712	43.561	1.04	9.046	45.231	0.0139	4.256
16	527	4068	207	1936	52.7	77.19	3.928	36.736	1.04	4.071	38.073	0.0128	8.158
17	528	4072	177	2422	52.8	77.12	3.352	45.871	1.04	3.477	47.583	0.0121	9.634
18	527	4072	173	2301	52.7	77.27	3.283	43.662	1.04	3.399	45.206	0.0153	12.486
19	527	4056	124	1314	52.7	76.96	2.353	24.934	1.04	2.446	25.917	0.0125	9.097
20	527	4065	236	2144	52.7	77.13	4.478	40.683	1.04	4.645	42.194	0.0145	8.514
												average	8.636
												standard deviation	4.324
												CV%	50.066

Table A-40: Results of Testing Input Yarn 9 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 9	**Wool/Nylon, R120/2 tex, (colour: Camel)**											**Test length= 60 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	674	3924	223	2352	67.4	58.22	3.309	34.896	1.03	3.410	35.963	0.0072	2.463
2	675	3927	169	1958	67.5	58.18	2.504	29.007	1.03	2.582	29.916	0.0063	2.741
3	674	3927	221	2331	67.4	58.26	3.279	34.585	1.03	3.377	35.615	0.0059	2.041
4	676	3922	178	2189	67.6	58.02	2.633	32.382	1.03	2.723	33.488	0.007	3.000
5	677	3932	196	2048	67.7	58.08	2.895	32.334	1.03	2.991	33.403	0.0072	2.808
6	675	3929	308	2431	67.5	58.21	4.563	30.341	1.03	4.703	31.275	0.0066	1.608
7	677	3937	111	2390	67.7	58.15	1.640	35.908	1.03	1.692	37.049	0.007	4.793
8	664	3930	197	2175	66.4	59.19	2.967	32.756	1.01	3.008	33.206	0.0065	2.518
9	675	3934	221	2153	67.5	58.28	3.274	31.896	1.03	3.371	32.837	0.0072	2.483
10	677	3936	300	1942	67.7	58.14	4.431	28.685	1.03	4.573	29.604	0.0064	1.564
11	677	3937	159	1761	67.7	58.15	2.349	26.012	1.03	2.423	26.838	0.0083	3.589
12	675	3936	221	2204	67.5	58.33	3.274	32.652	1.03	3.368	33.589	0.0075	2.599
13	676	3939	161	1864	67.6	58.22	2.382	27.574	1.03	2.454	28.415	0.008	3.556
14	678	3930	163	1866	67.8	58.10	2.404	27.522	1.03	2.483	28.423	0.0073	3.207
15	676	3936	250	2340	67.6	58.14	3.698	34.615	1.03	3.817	35.725	0.0069	2.111
16	677	3936	173	2288	67.7	58.14	2.555	33.796	1.03	2.637	34.878	0.0067	2.317
17	678	3930	180	2022	67.8	58.05	2.655	29.823	1.03	2.744	30.823	0.0072	2.989
18	676	3939	71	1974	67.6	58.14	1.050	29.201	1.03	1.084	30.137	0.0068	7.073
19	678	3941	168	1909	67.8	58.10	2.478	28.156	1.03	2.559	29.078	0.0074	3.199
20	678	3938	220	1991	67.8	58.13	3.245	29.366	1.03	3.349	30.312	0.0077	2.600
												average	2.963
												standard deviation	1.212
												CV%	40.90

Table A-41: Results of Testing Input Yarn 10 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 10		**Linen/cotton, R144/2 tex, (colour: Sand)**										**Test length= 55 mm**	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	470	2518	179	1371	47	53.57	3.809	29.170	1.03	3.910	29.946	0.0075	1.716
2	471	2539	218	1295	47.1	53.91	4.628	27.495	1.02	4.722	28.052	0.0074	1.371
3	468	2519	236	1493	46.8	53.82	5.043	31.902	1.02	5.153	32.598	0.0073	1.275
4	470	2521	183	1382	47	53.64	3.894	29.404	1.03	3.992	30.151	0.0073	1.638
5	470	2515	93	1174	47	53.51	1.979	24.979	1.03	2.034	25.674	0.0076	3.109
6	470	2533	140	1254	47	53.89	2.979	26.681	1.02	3.040	27.229	0.0072	2.042
7	468	2510	76	1158	46.8	53.63	1.624	24.744	1.03	1.665	25.375	0.0077	3.818
8	470	2529	298	1510	47	53.81	6.340	32.128	1.02	6.481	32.839	0.0073	1.013
9	471	2515	191	1422	47.1	53.40	4.055	30.191	1.03	4.177	31.097	0.008	1.724
10	474	2517	196	1562	47.4	53.10	4.135	32.954	1.04	4.283	34.132	0.0079	1.643
11	472	2529	133	1321	47.2	53.58	2.818	27.987	1.03	2.892	28.729	0.008	2.443
12	471	2516	202	1286	47.1	53.42	4.289	27.304	1.03	4.416	28.112	0.0082	1.626
13	472	2520	197	1448	47.2	53.39	4.174	30.678	1.03	4.300	31.603	0.0084	1.76
14	471	2519	197	1232	47.1	53.48	4.183	26.157	1.03	4.301	26.900	0.0079	1.573
15	473	2522	74	1569	47.3	53.32	1.564	33.171	1.03	1.614	34.217	0.0082	4.522
16	471	2518	187	1441	47.1	53.46	3.970	30.594	1.03	4.085	31.475	0.0081	1.786
17	472	2522	178	1503	47.2	53.43	3.771	31.843	1.03	3.882	32.778	0.0083	1.923
18	469	2520	134	1332	46.9	53.73	2.857	28.401	1.02	2.925	29.071	0.008	2.426
19	471	2522	247	1507	47.1	53.55	5.244	31.996	1.03	5.387	32.865	0.0082	1.369
20	471	2520	167	1193	47.1	53.50	3.546	25.329	1.03	3.645	26.038	0.0078	1.797
												average	2.029
												standard deviation	0.872
												CV%	42.973

Table A-42: Results of Testing Input Yarn 11 for Bending Using the Improved Bending Frame and the Digital Image Analysis

Yarn number 11		Lambswool, 1/12s, 83 tex (colour: Rose),										Test length=45 mm	
specimen	**10 mm = in pixel**	**L (pixel)**	**y (pixel)**	**x (pixel)**	**1 mm= in pixel**	**L (mm)**	**y (mm)**	**x (mm)**	**L set /L measured**	**y corrected**	**x corrected**	**W (g)**	**B (g mm^2)**
1	532	2355	220	1476	53.2	44.27	4.135	27.744	1.02	4.204	28.204	0.0039	0.451
2	530	2344	186	1081	53	44.23	3.509	20.396	1.02	3.571	20.753	0.0039	0.494
3	530	2332	160	1329	53	44.00	3.019	25.075	1.02	3.087	25.645	0.0036	0.575
4	533	2347	159	1339	53.3	44.03	2.983	25.122	1.02	3.049	25.673	0.0032	0.518
5	533	2344	180	1441	53.3	43.98	3.377	27.036	1.02	3.456	27.664	0.0029	0.410
6	529	2356	140	1258	52.9	44.54	2.647	23.781	1.01	2.674	24.028	0.0032	0.583
7	752	3333	282	1840	75.2	44.32	3.750	24.468	1.02	3.807	24.842	0.0032	0.413
8	534	2349	146	909	53.4	43.99	2.734	17.022	1.02	2.797	17.414	0.0034	0.472
9	535	2357	236	1776	53.5	44.06	4.411	33.196	1.02	4.506	33.908	0.0027	0.238
10	533	2356	154	1275	53.3	44.20	2.889	23.921	1.02	2.941	24.353	0.0028	0.466
11	535	2346	143	1150	53.5	43.85	2.673	21.495	1.03	2.743	22.059	0.0034	0.582
12	533	2360	170	1472	53.3	44.28	3.189	27.617	1.02	3.242	28.068	0.0034	0.511
13	535	2355	160	1588	53.5	44.02	2.991	29.682	1.02	3.057	30.344	0.0034	0.516
14	534	2347	164	1336	53.4	43.95	3.071	25.019	1.02	3.144	25.616	0.004	0.628
15	535	2356	84	1447	53.5	44.04	1.570	27.047	1.02	1.604	27.638	0.0036	1.099
16	535	2354	157	1708	53.5	44.00	2.935	31.925	1.02	3.001	32.651	0.0038	0.538
17	535	2344	206	1334	53.5	43.81	3.850	24.935	1.03	3.955	25.610	0.003	0.374
18	533	2363	143	1255	53.3	44.33	2.683	23.546	1.02	2.723	23.900	0.0035	0.625
19	535	2362	277	1403	53.5	44.15	5.178	26.224	1.02	5.277	26.729	0.0032	0.299
20	533	2353	66	1706	53.3	44.15	1.238	32.008	1.02	1.262	32.626	0.0035	1.180
												average	0.549
												standard deviation	0.226
												CV%	41.236

Appendix B: The Results of The Measurements of the Quality Parameters of the Bouclé and Semi-bouclé Yarns

Table B-1: Data Collected for the Geometrical Model of Multi-thread of Fancy Yarn: Part I

Fancy Yarn	Measurement	L (mm)	n (helical part)	m (sinusoidal part)	W (wpm)	H_2 (helical part)	H_1 (sinusoidal part)
1	1	6.50	11	6	17	1.23	2.94
	2	6.78				0.96	2.33
	3	7.69				1.10	2.70
Average		6.99				1.10	2.66
2	1	3.21	17	11	28	0.70	1.60
	2	3.72				0.50	1.88
	3	2.91				0.76	2.14
average		3.28				0.65	1.87
3	1	3.87	24	6	30	0.62	2.84
	2	4.43				0.64	3.24
	3	2.91				0.88	2.29
average		3.74				0.71	2.79
4	1	6.40	9.5	10	19.5	0.52	4.94
	2	5.31				0.46	2.67
	3	4.13				0.69	3.42
	4	4.55					
average		5.10				0.56	3.68
5	1	4.09	17	10	27	0.47	1.86
	2	3.72				0.39	1.49
	3	3.31				0.80	3.79
	4	3.65					2.80
average		3.69				0.55	2.49

Table B-2: Data Collected for the Geometrical Model of Multi-thread of Fancy Yarn: Part II

Fancy Yarn	Measurement	L (mm)	n (helical part)	m (sinusoidal part)	W (wpm)	H_2 (helical part)	H_1 (sinusoidal part)
6	1	3.83	9	23	31	0.72	1.70
	2	3.98				0.83	2.04
	3	3.04				0.76	1.03
	4					0.52	1.13
average		3.62				0.71	1.48
7	1	6.36	10.5	9	19.5	0.94	4.06
	2	5.19				0.92	3.26
	3	4.47				1.22	4.10
	4					0.79	3.50
average		5.34				0.97	3.73
8	1	5.21	10.5	7	17.5	0.77	4.77
	2	5.24				0.69	1.90
	3	7.67				0.75	4.04
	4					0.62	4.25
average		6.04				0.71	3.74
9	1	5.33	15	6	21	1.07	4.25
	2	4.70				0.58	3.22
	3	4.70				0.62	4.38
	4					0.49	3.95
average		4.91				0.69	3.95
10	1	5.78	13	9	22	0.64	2.41
	2	5.07				0.62	4.32
	3	5.99				0.45	3.22
average		5.61				0.57	3.32

Table B-3: Data Collected for the Geometrical Model of Multi-thread of Fancy Yarn: Part III

Fancy Yarn	Measurement	L (mm)	n (helical part)	m (sinusoidal part)	W (wpm)	H_2 (helical part)	H_1 (sinusoidal part)
11	1	4.70	15	7	22	0.69	4.06
	2	4.30				0.56	5.07
	3	4.08				0.56	4.07
average		4.36				0.60	4.40
12	1	5.63	12	8	20	0.64	3.11
	2	5.28				0.56	4.55
	3	5.03				0.52	3.78
average		5.31				0.57	3.81
13	1	3.84	22	3	25	0.41	3.03
	2	3.24				0.37	1.83
	3	4.30				0.69	2.51
average		3.79				0.49	2.46
14	1	4.94	20	0	20	0.71	0.00
	2	4.49				0.60	
	3	5.22				0.49	
average		4.88				0.60	
15	1	4.94	18.50	3	21.50	0.64	1.63
	2	5.11				0.56	2.71
	3	5.07				0.64	2.47
average		5.04				0.61	2.27

Table B-4: the Influence of the Rotational Speed on the First Spinning Zone and the Size of Bouclé Profile (mm^2) when the Overfeed Ratio and the Number of Wraps were Fixed

Sample number	Standard Trial Order and Yarn Designation				
	Yarn 1	**Yarn 2**	**Yarn 3**	**Yarn 4**	**Yarn 5**
	St. 1/ run. 5	**St. 2/ run. 4**	**St. 3/ run. 9**	**St. 4/ run. 8**	**St. 5 /run. 3**
1	32.72	36.73	43.43	10.28	11.19
2	24.58	17.51	9.89	12.64	26.83
3	7.99	17.78	15.44	6.46	15.23
4	8.67	19.00	22.90	9.28	10.31
5	15.77	30.14	18.01	14.14	21.58
6	21.40	10.21	18.32	9.88	8.58
7	32.15	10.45	22.75	12.87	6.45
8	26.23	37.75	10.08	7.56	17.17
9	26.81	22.76	32.20	9.83	7.81
10	25.87	18.91	8.79	11.14	6.82
11	10.14	17.72	25.06	9.75	6.08
12	18.46	12.25	8.41	9.15	13.28
13	28.75	12.94	32.41	9.79	7.47
14	34.85	17.23	9.69	8.07	9.86
15	26.52	24.48	11.08	10.90	8.11
16	45.16	26.17	14.97	7.85	10.23
Average	24.13	20.75	18.96	9.97	11.69
SD	10.14	8.48	10.25	2.04	5.88

Table B-5: the Influence of the Rotational Speed on the First Spinning Zone and the Number of Bouclé and Semi-bouclé Profiles per Decimetre when the Overfeed Ratio and the Number of Wraps were Fixed

Sample Number	Standard Trial Order and Yarn Designation				
	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5
	St. 1/ run. 5	St. 2/ run. 4	St. 3/ run. 9	St. 4/ run. 8	St. 5/ run. 3
1	5	6	9	7	13
2	4	4	6	13	11
3	4	5	6	8	12
4	5	5	6	10	9
5	5	4	6	8	11
6	3	6	5	10	9
7	4	7	6	11	8
8	4	8	6	4	9
9	7	4	6	10	8
10	5	6	5	9	6
11	4	6	7	7	12
12	6	5	6	7	10
13	7	6	5	5	12
14	5	6	6	6	9
15	5	4	6	10	8
Average	4.88	5.46	6.06	8.33	9.80
SD	1.13	1.19	0.96	2.41	1.97

Table B-6: Influence of Rotational Speed, Thickness of the Effect Thread and Number of the Effect-thread Helices on the Size of Bouclé Profiles (mm^2) for Group I of Fancy Yarn

sample	Setting 1	Setting 2	Setting 3	Setting 4	Setting 5	Setting 6
			Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	No yarn was made	No yarn was made	34.74	13.99	11.60	6.93
2			13.80	16.41	7.93	5.56
3			27.57	6.41	8.21	10.41
4			25.80	8.85	11.52	8.26
5			52.90	17.53	15.26	7.64
6			9.25	15.58	9.66	7.13
7			13.11	16.51	7.83	7.94
8			8.87	10.59	13.49	8.99
9			12.38	17.84	13.75	7.13
10			8.72	9.52	11.80	11.66
11			13.81	12.71	11.54	11.23
12			91.12	12.36	7.37	10.09
13			7.81	9.13	11.27	6.33
14			8.68	9.53	11.35	8.30
15			20.89	12.79	14.03	5.50
16			32.90	11.05	6.66	6.18
Average	*	*	23.90	12.55	10.83	8.08
SD	*	*	21.91	3.49	2.63	1.93

Table B-7: Influence of Rotational Speed, Thickness of the Effect Thread and Number of the Effect-thread Helices on the Size of Bouclé Profiles (mm^2) for Group II of Fancy Yarn

Sample	Setting 1	Setting 2	Setting 3	Setting 4	Setting 5	Setting 6
		Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	No yarn was made	19.81	24.79	17.10	10.46	9.57
2		26.89	9.78	7.65	9.65	9.59
3		20.39	8.82	5.93	9.18	6.12
4		21.26	11.77	7.54	9.77	7.36
5		24.42	13.64	8.15	6.43	10.27
6		11.18	23.07	7.59	5.32	10.54
7		18.66	17.54	6.74	16.53	7.15
8		16.01	9.77	7.14	7.14	6.18
9		27.18	15.85	10.74	5.53	6.49
10		41.32	8.66	8.95	8.51	8.92
11		10.96	9.87	9.09	7.28	7.92
12		14.52	10.30	10.79	9.31	7.65
13		14.33	16.66	18.24	9.21	8.67
14		20.73	19.45	7.61	8.45	10.23
15		36.02	15.33	18.92	8.76	10.63
16		11.98	10.73	5.53	7.72	7.92
Average	*	20.98	14.13	9.86	8.70	8.45
SD	*	8.64	5.10	4.34	2.57	1.57

Table B-8: Influence of Rotational Speed, Thickness of the Effect Thread and Number of the Effect-thread Helices on the Number of Bouclé Profiles per Decimetre for Group I of Fancy Yarn

Sample	Setting 1	Setting 2	Setting 3	Setting 4	Setting 5	Setting 6
			Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	No yarn was made	No yarn was made	2	7	7	9
2			4	8	8	13
3			6	4	11	9
4			5	5	8	10
5			4	5	9	9
6			4	6	10	8
7			5	5	8	8
8			2	8	7	7
9			5	6	8	10
10			4	5	9	10
11			6	8	8	10
12			5	7	8	8
13			5	8	6	7
14			5	7	8	10
15			7	6	10	10
Average	*	*	4.6	6.33	8.33	9.2
SD	*	*	1.35	1.34	1.29	1.52

Table B-9: Influence of Rotational Speed, Thickness of the Effect Thread and Number of the Effect-thread Helices on the Number of Bouclé Profiles Per Decimetre for Group II of Fancy Yarn

Sample	Setting 1	Setting 2	Setting 3	Setting 4	Setting 5	Setting 6
		Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	No yarn was made	5	6	8	7	11
2		7	6	8	9	10
3		4	7	8	8	10
4		7	7	10	11	11
5		7	7	8	8	9
6		4	7	7	10	7
7		6	9	8	9	9
8		6	6	11	7	9
9		5	6	8	7	8
10		5	6	8	7	10
11		5	8	7	10	8
12		4	9	8	10	7
13		7	7	11	8	8
14		5	8	8	7	10
15		6	9	6	8	8
Average	*	5.53	7.2	8.26	8.4	9
SD	*	1.12	1.14	1.36	1.35	1.31

Table B-10: The Effect of Bending Stiffness of the Effect thread: the Main Experiment

Sample	Size of Bouclé Profiles (mm^2)				Number of Bouclé and Semi-bouclé Projections (dm^{-1})			
	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 1	Yarn 2	Yarn 3	Yarn 4
1	15.42	15.69	21.44	22.41	15	15	10	9
2	16.49	11.60	20.29	26.17	13	8	9	5
3	24.30	17.80	17.36	15.72	17	11	11	4
4	14.23	11.89	17.08	9.50	15	8	5	4
5	11.45	21.35	13.98	15.25	8	13	11	4
6	19.41	11.49	13.51	13.02	14	15	11	9
7	13.70	10.39	18.09	11.98	16	18	10	6
8	13.77	22.11	21.36	16.12	11	12	11	9
9	13.03	13.58	16.32	11.85	17	15	8	4
10	11.43	21.55	17.06	17.04	13	16	10	8
11	20.30	14.20	16.07	23.60	16	12	11	7
12	9.48	16.12	17.55	15.19	17	13	8	6
13	11.64	15.23	12.10	20.24	10	7	12	7
14	17.87	13.23	10.09	20.31	19	12	9	7
15	30.30	11.51	13.79	18.60	13	11	9	8
16	13.87	12.08	14.43	22.52				
17	15.64	14.56	19.65	15.03				
18	12.72	13.90	21.90	19.39				
19	15.42	13.68	12.80	15.17				
20	11.24	12.06	18.48	17.87				
21	11.30	26.16	15.99	23.55				
22	12.99	19.12	13.90	21.21				
23	17.07	17.76	16.72	19.86				
24	13.87	19.11	18.25	22.32				
25	12.38	8.68	15.27	23.72				
26	10.57	11.84	14.82	15.90				
27	13.46	11.11	16.12	19.81				
28	15.93	21.35	14.91	13.01				
29	9.79	10.94	18.93	33.31				
30	11.08	13.24	19.64	23.73				
31	16.90	13.47	17.95	21.76				
Average	14.74	15.06	16.64	18.88	14.27	12.4	9.66	6.46
SD	4.37	4.2	2.86	5	2.98	3.13	1.76	1.92

Table B-11: The Effect of Bending Stiffness of the Effect thread: the Confirmation Trials

sample	Size of Bouclé Profiles (mm^2)		Number of Bouclé and Semi-bouclé Projections (dm^{-1})	
	Yarn 1	Yarn 2	Yarn 1	Yarn 2
1	14.66	14.73	10	9
2	12.68	13.25	11	11
3	29.00	11.50	14	11
4	13.55	11.90	19	8
5	19.14	9.59	13	10
6	11.99	24.80	11	10
7	14.71	25.37	11	7
8	8.67	13.81	11	8
9	9.51	12.92	12	9
10	10.15	12.54	14	9
11	10.22	14.38	13	10
12	11.25	11.05	13	15
13	7.89	20.83	10	14
14	11.78	9.71	13	13
15	10.86	23.64	9	11
16	11.89	11.17		
17	25.70	19.75		
18	10.68	18.87		
19	13.29	8.62		
20	12.81	14.16		
21	15.78	16.17		
22	9.36	15.61		
23	10.32	19.19		
24	11.50	13.43		
25	14.12	14.50		
26	15.46	11.58		
27	15.98	11.69		
28	11.98	12.86		
29	22.70	13.50		
30	14.50	15.74		
31	17.09	11.62		
Average	13.85	14.79	11.79	10
SD	4.79	4.39	1.58	1.24

Table B-12: The Effect of Bending Stiffness of the Core Thread on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	10.51	11.54	15.06	8.85	12.52	8.61
2	11.50	10.87	9.25	15.22	6.87	10.85
3	8.17	14.60	16.07	5.69	11.49	8.50
4	15.87	12.93	30.69	12.85	19.46	17.36
5	7.55	8.59	10.78	11.56	16.93	11.91
6	8.90	21.64	7.81	14.99	11.61	14.74
7	15.72	11.13	13.90	14.92	8.32	12.37
8	5.35	11.29	18.51	6.25	8.18	12.40
9	6.69	10.63	14.55	9.92	9.42	18.26
10	4.18	10.43	17.09	13.93	8.71	6.80
11	12.06	7.65	14.66	13.00	10.78	11.36
12	8.87	7.58	10.78	12.90	25.18	10.83
13	9.08	18.57	9.32	12.59	12.47	9.70
14	6.96	4.94	8.49	10.98	9.94	6.25
15	13.83	10.75	12.75	17.21	12.06	8.74
16	9.68	6.24	12.39	10.84	6.50	5.67
Average	9.68	11.21	13.88	11.98	11.90	10.90
SD	3.54	4.29	5.49	3.17	4.92	3.64

Table B-13: The Effect of Bending Stiffness of the Core Thread on the Circularity Ratio of Bouclé Profiles

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	0.50	0.82	0.60	0.72	0.31	0.43
2	0.61	0.60	0.64	0.20	0.35	0.65
3	0.28	0.50	0.36	0.53	0.79	0.36
4	0.48	0.45	0.81	0.42	0.22	0.51
5	0.19	0.25	0.73	0.98	0.53	0.45
6	0.73	0.76	0.53	0.64	0.44	0.42
7	0.26	0.57	0.29	0.43	0.43	0.44
8	0.83	0.76	0.88	0.55	0.49	0.49
9	0.71	0.57	0.42	0.51	0.47	0.71
10	0.42	0.40	0.41	0.56	0.52	0.71
11	0.70	0.61	0.80	0.73	0.68	0.61
12	0.44	0.19	0.39	0.37	0.41	0.80
13	0.82	0.67	0.42	0.53	0.57	0.78
14	0.46	0.74	0.23	0.79	0.58	0.49
15	0.39	0.88	0.33	0.26	0.75	0.46
16	0.52	0.58	0.76	0.39	0.60	0.60
Average	0.52	0.59	0.54	0.54	0.51	0.56
SD	0.20	0.19	0.21	0.20	0.15	0.14

Table B-14: The Effect of Bending Stiffness of the Core Thread on the Number of Bouclé Profiles per Decimetre

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	9	7	8	7	7	9
2	9	9	8	7	11	9
3	11	8	7	10	7	6
4	10	8	8	7	9	8
5	9	9	6	7	9	8
6	8	8	11	6	8	10
7	9	7	9	7	9	10
8	9	8	7	9	7	9
9	8	9	7	7	10	7
10	9	8	10	11	8	11
11	8	7	7	8	12	8
12	9	6	7	8	9	9
13	9	7	8	9	8	6
14	6	7	7	10	8	8
15	11	11	10	11	8	9
Average	8.9	7.9	8	8.2	8.6	8.4
SD	1.2	1.2	1.4	1.6	1.4	1.4

Table B-15: The Effect of the Overfeed Ratio on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Confirmation Yarn
1	13.47	23.00	21.63	24.75	35.04	26.93
2	17.70	15.43	14.92	46.98	59.12	17.22
3	14.75	18.32	22.74	31.49	22.98	29.61
4	14.74	14.21	11.86	19.01	22.79	30.08
5	14.22	17.50	14.64	28.49	21.39	32.25
6	10.33	11.82	16.20	41.35	32.85	18.80
7	19.27	9.65	19.80	18.46	14.83	16.88
8	9.33	13.08	21.56	20.59	45.26	11.58
9	12.97	14.15	18.85	51.11	47.59	20.99
10	14.73	13.83	13.30	46.77	22.66	12.97
11	11.48	13.09	18.94	25.99	42.05	21.63
12	13.46	13.86	25.32	22.45	20.12	24.61
13	17.15	15.26	21.94	27.41	12.76	22.44
14	10.07	16.87	27.05	19.65	24.80	28.80
15	11.24	19.33	26.56	30.57	16.30	14.59
16	16.33	15.35	18.29	21.70	19.30	17.76
17	13.78	18.02	19.93	62.39	22.93	22.99
18	8.91	20.35	15.82	31.75	23.89	16.91
19	12.58	24.15	17.09	17.94	56.55	18.03
20	13.94	15.46	17.55	37.78	20.60	15.12
21	14.32	14.12	36.78	14.33	25.34	19.77
22	15.64	10.41	18.08	28.11	44.41	23.61
23	11.29	18.60	15.75	36.96	46.60	11.67
24	8.97	18.11	10.75	32.61	76.64	12.14
25	19.73	9.91	20.35	21.22	32.60	23.91
26	10.03	23.68	24.28	23.89	57.53	15.99
27	8.17	16.70	26.50	21.83	15.29	16.37
28	15.57	18.93	31.05	28.95	18.41	17.62
29	17.76	23.75	41.60	24.71	31.90	19.95
30	11.37	10.81	36.67	42.49	17.15	17.73
31	17.49	16.83	41.64	23.65	62.78	13.86
Average	13.57	16.28	22.18	29.85	32.66	19.77
SD	3.17	4.03	8.15	11.17	16.79	5.64

Table B-16: The Effect of the Overfeed Ratio on the Circularity Ratio of Bouclé Profiles

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Confirmation Yarn
1	0.65	0.39	0.59	0.23	0.83	0.82
2	0.81	0.64	0.75	0.24	0.62	0.77
3	0.91	0.47	0.41	0.52	0.70	0.27
4	0.48	0.47	0.47	0.80	0.61	0.42
5	0.62	0.35	0.52	0.58	0.37	0.45
6	0.62	0.73	0.25	0.34	0.77	0.88
7	0.34	0.35	0.62	0.44	0.62	0.61
8	0.62	0.56	0.29	0.29	0.58	0.49
9	0.48	0.95	0.29	0.32	0.65	0.38
10	0.47	0.54	0.67	0.19	0.37	0.56
11	0.48	0.58	0.74	0.37	0.40	0.41
12	0.59	0.53	0.34	0.51	0.64	0.39
13	0.93	0.56	0.55	0.40	0.48	0.94
14	0.80	0.53	0.40	0.47	0.78	0.55
15	0.73	0.66	0.58	0.47	0.54	0.69
16	0.56	0.56	0.48	0.52	0.31	0.70
17	0.61	0.73	0.74	0.37	0.58	0.27
18	0.84	0.55	0.59	0.26	0.34	0.90
19	0.44	0.55	0.29	0.41	0.48	0.48
20	0.42	0.38	0.50	0.70	0.35	0.57
21	0.41	0.65	0.80	0.59	0.22	0.67
22	0.80	0.53	0.73	0.71	0.44	0.34
23	0.69	0.76	0.74	0.62	0.69	0.87
24	0.79	0.38	0.35	0.80	0.81	0.70
25	0.37	0.55	0.53	0.53	0.78	0.46
26	0.75	0.55	0.49	0.78	0.64	0.46
27	0.38	0.49	0.37	0.61	0.59	0.70
28	0.39	0.41	0.79	0.65	0.55	0.37
29	0.46	0.51	0.25	0.71	0.59	0.48
30	0.49	0.76	0.72	0.46	0.51	0.32
31	0.57	0.47	0.47	0.62	0.56	0.75
Average	0.60	0.55	0.53	0.50	0.56	0.57
SD	0.17	0.14	0.17	0.18	0.16	0.20

Table B-17: The Effect of the Overfeed Ratio on the Number of Bouclé and Semi-bouclé Profiles (dm^{-1})

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Confirmation Yarn
1	16	12	19	14	22	16
2	14	12	17	15	16	15
3	9	16	20	17	22	16
4	9	11	18	20	17	17
5	11	15	16	16	16	16
6	10	13	14	17	17	14
7	13	15	20	17	14	15
8	12	14	15	17	13	14
9	10	16	11	15	14	15
10	13	16	10	18	17	16
11	13	11	17	14	18	14
12	14	13	14	16	13	15
13	10	11	15	14	14	16
14	10	14	18	13	17	15
15	15	12	12	16	16	16
Average	11.93	13.40	15.73	15.93 [26]	16.4	15.33
SD	2.25	1.88	3.13	1.83	2.77	0.90

[26] Bouclé and semi-bouclé projections started to cluster in yarn 4 and yarn 5. Therefore, the ShF does not represent the visual aesthetic fancy bulkiness of the yarn. Instead, it only accounts for the real or actual fancy bulkiness which sometimes is not evenly distributed along the yarn length, e.g. the case of these two cones.

Table B-18: The Effect of the Number of Wraps on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6	Yarn 7	Confirmation Yarn
1	21.04	20.23	14.10	27.50	20.32	13.07	15.15	14.03
2	24.96	16.13	19.10	12.49	19.10	18.76	20.31	14.84
3	29.70	11.04	13.94	20.44	26.84	12.74	17.32	11.84
4	24.60	14.89	18.57	16.62	14.99	12.39	16.09	22.28
5	32.95	20.20	17.25	13.22	11.19	8.17	15.71	24.32
6	42.73	22.29	15.58	12.12	13.82	28.61	10.59	10.68
7	17.36	18.63	19.40	21.88	15.12	15.44	16.29	14.99
8	34.73	16.18	14.89	15.03	19.05	14.80	11.19	10.43
9	20.32	9.24	22.59	12.43	15.80	21.87	14.48	15.44
10	11.80	27.32	14.39	14.63	16.09	15.61	12.89	13.76
11	11.98	15.91	16.31	17.15	17.61	20.77	12.60	15.53
12	22.25	20.37	18.71	12.01	15.45	11.24	11.22	15.47
13	17.86	12.50	18.66	9.59	18.03	14.00	17.57	11.09
14	21.80	17.49	22.78	21.41	8.28	12.08	14.26	15.15
15	11.37	15.34	24.85	14.87	20.45	11.82	16.02	15.58
16	31.60	10.72	14.83	12.95	22.41	16.34	14.36	18.43
17	20.92	18.89	19.99	19.69	16.95	15.26	10.64	13.09
18	11.64	25.51	23.82	19.05	11.51	18.22	12.68	14.02
19	21.72	9.73	24.99	18.52	18.81	12.93	12.88	25.64
20	13.66	12.82	14.01	22.53	17.28	22.81	17.74	17.97
21	26.49	50.69	14.18	22.69	17.24	16.47	10.51	14.68
22	20.15	13.43	35.19	14.14	16.99	18.39	15.91	16.05
23	29.98	15.06	15.81	23.20	12.65	10.73	15.58	16.48
24	12.41	13.16	23.90	14.62	26.67	15.43	16.18	12.75
25	15.62	10.21	13.47	16.88	13.20	11.27	19.61	12.80
26	25.23	16.00	26.80	15.69	14.30	12.79	10.37	11.13
27	24.39	7.70	12.18	20.06	13.37	12.21	11.47	9.58
28	18.08	20.69	13.96	12.25	13.31	13.28	11.73	16.43
29	20.44	21.72	24.90	15.96	13.75	15.42	9.21	12.50
30	19.34	23.94	13.78	17.34	15.85	7.78	15.00	13.78
31	13.76	22.36	14.50	18.75	9.14	18.92	11.09	18.72
Average	21.64	17.76	18.63	16.96	16.31	15.15	14.09	15.14
SD	7.62	7.91	5.28	4.17	4.26	4.41	2.90	3.77

Table B-19: The Effect of the Number of Wraps on the Number of Bouclé Profiles (dm^{-1})

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6	Yarn 7	Confirmation Yarn
1	14	11	14	13	15	14	13	21
2	14	14	13	17	15	15	15	17
3	16	15	14	16	16	12	14	16
4	14	18	16	12	10	13	15	15
5	13	13	12	14	16	15	10	14
6	15	14	17	19	11	10	13	11
7	15	13	16	18	13	15	11	19
8	9	12	12	17	14	19	12	12
9	13	16	14	13	14	14	14	15
10	12	17	12	13	14	16	15	14
11	12	10	14	15	14	14	10	18
12	13	14	15	12	12	13	14	15
13	13	14	14	10	11	18	14	12
14	13	14	14	14	17	15	18	9
15	15	14	14	16	15	19	13	13
Average	13.40	13.93	14.07	14.07	13.80	14.80	13.38	14.73
SD	1.68	2.08	1.48	2.53	2.04	2.48	2.02	3.17

Table B-20: Effect of the Interaction between the Structural Parameters on the Size of Bouclé Profiles (mm^2)

Sample	Standard Trial Order/ Randomised Trial Order								
	St. 1/ run. 5	St. 2/ run. 4	St. 3/ run. 9	St. 4/ run. 8	St. 5/ run. 3	St. 6/ run. 6	St. 7/ run. 1	St. 8/ run. 2	St. 9/ run. 7
1	14.45	15.78	81.57	62.58	24.88	41.52	21.86	27.35	13.97
2	11.07	13.85	12.40	22.80	37.79	23.83	23.81	19.23	15.54
3	12.61	19.91	10.48	45.52	26.95	28.33	23.27	12.59	14.03
4	11.10	16.26	8.20	46.76	11.65	29.84	18.53	17.62	10.94
5	10.11	13.63	15.11	20.43	17.18	27.02	15.98	22.20	31.85
6	13.85	12.71	70.23	23.66	29.37	28.15	29.86	15.36	23.52
7	11.48	10.10	21.02	22.17	24.53	24.24	15.75	24.37	10.55
8	14.58	10.11	19.65	25.19	32.77	40.46	39.82	30.67	13.48
9	11.29	18.49	17.99	19.14	9.98	17.11	17.39	35.85	16.44
10	12.87	15.00	53.42	29.81	28.59	37.41	19.04	11.47	9.98
11	12.45	22.84	31.91	19.87	11.65	84.25	17.11	26.33	9.54
12	9.82	15.11	20.69	31.44	11.13	16.75	17.08	16.12	17.92
13	14.01	17.38	13.77	19.78	17.24	23.29	13.48	40.69	9.78
14	19.12	13.05	27.49	24.73	19.06	13.02	28.10	45.71	16.30
15	13.02	19.26	25.19	46.01	19.83	47.23	20.22	11.35	14.91
16	13.50	14.86	57.12	50.30	39.81	23.70	9.71	59.05	23.45
17	12.60	15.77	38.17	36.64	19.26	23.37	14.78	23.48	13.19
18	15.06	10.93	30.85	35.64	27.99	33.07	19.86	23.79	12.81
19	14.64	9.35	15.79	21.35	17.41	40.72	19.13	15.60	12.35
20	10.96	10.73	116.91	12.86	13.66	29.97	17.33	24.83	13.99
21	16.06	19.42	19.29	21.63	13.91	29.86	36.80	58.16	12.00
22	15.16	13.72	34.04	21.85	21.94	29.71	21.63	23.05	10.87
23	9.69	11.34	45.06	10.55	19.93	35.39	20.78	34.95	11.02
24	15.25	14.00	34.46	67.36	13.41	26.62	12.28	10.15	12.81
25	13.32	20.34	61.19	35.28	9.76	46.12	12.55	15.91	14.51
26	10.49	10.88	40.30	26.46	24.04	49.46	16.28	23.82	15.10
27	18.36	9.32	44.45	30.82	17.75	30.65	28.56	19.65	24.03
28	15.56	26.15	30.69	12.99	14.12	27.33	29.98	23.61	7.90
29	11.90	17.60	23.34	12.01	13.40	49.72	13.71	26.36	9.49
30	11.23	15.09	44.33	39.68	24.38	47.39	25.90	31.51	11.35
31	16.50	16.96	107.99	23.88	17.25	16.16	26.26	18.47	19.66
Average	13.29	15.16	37.84	29.65	20.34	32.96	20.87	25.46	14.62
SD	2.40	4.08	26.82	14.16	7.93	13.91	7.09	12.24	5.23

Table B-21: Effect of the Interaction between the Structural Parameters on the Number of Bouclé Profiles (dm^{-1})

Measurement	Standard Trial Order/ Randomised Trial Order								
	St. 1/ run. 5	St. 2/ run. 4	St. 3/ run. 9	St. 4/ run. 8	St. 5/ run. 3	St. 6/ run. 6	St. 7/ run. 1	St. 8/ run. 2	St. 9/ run. 7
1	23	9	4	10	10	10	22	19	4
2	16	12	4	8	11	10	22	10	5
3	19	15	7	9	12	15	27	16	6
4	18	10	5	6	17	10	25	19	6
5	17	14	6	7	19	11	21	16	3
6	16	13	5	9	14	12	22	21	8
7	19	11	10	8	15	12	18	19	5
8	14	9	10	8	12	9	17	13	4
9	16	12	3	9	19	10	28	19	5
10	21	12	7	6	16	10	23	15	5
11	13	10	8	8	11	7	21	16	5
12	15	12	4	4	16	10	23	19	5
13	13	8	5	7	11	12	13	19	4
14	16	11	7	8	17	9	23	17	6
15	11	12	5	7	13	7	19	14	7
Average	13.29	15.16	37.84	29.65	20.34	32.96	20.87	25.46	14.62
SD	2.40	4.08	26.82	14.16	7.93	13.91	7.09	12.24	5.23

Table B-22: Effect of the Core Thread Tension on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5
1	29.17	17.75	20.94	25.85	99.59
2	22.70	11.96	17.71	24.70	27.50
3	31.13	19.74	13.90	25.63	13.85
4	13.55	16.04	13.98	11.88	23.33
5	35.84	9.92	19.56	20.55	86.01
6	11.97	18.41	11.69	23.37	38.22
7	22.41	17.79	22.86	24.28	18.35
8	13.76	23.51	18.83	17.16	33.00
9	12.69	28.92	21.38	18.86	18.95
10	15.73	24.01	17.89	25.20	18.26
11	15.85	11.00	32.71	27.03	14.78
12	17.71	10.93	52.84	13.67	39.97
13	26.59	23.67	41.42	23.16	97.53
14	21.21	8.05	37.71	36.62	61.16
15	13.69	16.62	23.40	25.05	80.52
16	7.45	24.70	24.57	13.30	37.17
Average	19.47	17.69	24.46	22.27	44.26
SD	7.95	6.17	11.23	6.24	30.52

Table B-23: Effect of the Core Thread Tension on the Number of Bouclé and Semi-bouclé Profiles (dm^{-1})

Sample	**Yarn 1**	**Yarn 2**	**Yarn 3**	**Yarn 4**	**Yarn 5**
1	32	34	30	27	23
2	39	35	30	26	19
3	38	37	29	25	20
4	41	38	22	31	20
5	36	38	16	28	23
6	39	33	24	23	22
7	37	43	28	23	29
8	36	30	23	25	24
9	33	37	25	25	20
10	36	30	25	33	22
Average	36.7	35.5	25.2	26.6	22.2
SD	2.75	3.98	4.34	3.27	2.9

Table B-24: Effect of Width of the Base of the Spinning Triangle on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5
1	10.02	12.44	21.93	15.72	16.54
2	15.99	13.34	11.61	10.86	23.41
3	12.80	13.31	31.46	22.38	23.90
4	11.81	14.93	14.65	19.78	8.36
5	17.53	14.01	13.82	11.04	16.03
6	19.39	14.33	5.66	12.16	22.24
7	16.52	6.80	9.62	9.75	15.55
8	17.19	15.53	11.47	16.45	14.63
9	8.50	15.59	5.95	6.74	20.37
10	17.39	20.07	9.63	11.51	10.33
11	8.49	15.35	7.81	12.68	12.03
12	9.51	10.09	15.47	10.22	17.94
13	15.38	13.18	9.04	17.52	7.32
14	10.45	25.61	8.55	14.65	7.92
15	9.89	15.17	16.15	12.32	29.49
Average	13.39	14.65	12.85	13.59	16.40
SD	3.80	4.19	6.72	4.15	6.59

Table B-25: Effect of Width of the Base of the Spinning Triangle on the Number of Bouclé and Semi-bouclé Profiles (dm^{-1})

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5
1	9	7	7	9	7
2	9	8	9	7	5
3	8	10	8	9	8
4	7	7	7	7	4
5	6	8	12	8	7
6	8	8	6	7	6
7	6	6	9	8	4
8	7	6	8	6	7
9	7	9	7	7	6
10	7	6	5	6	9
11	8	7	8	7	7
12	8	7	9	7	7
13	7	5	7	8	6
14	6	8	8	8	8
15	7	7	7	6	7
Average	7.3	7.2	7.8	7.3	6.5
SD	0.9	1.2	1.6	0.9	1.4

Table B-26: Effect of the Variability of the G&D Hollow-spindle Machine on the Size of Bouclé Profiles (mm^2)

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	24.90	21.95	16.18	14.05	19.17	16.33
2	9.31	21.61	39.17	27.20	15.65	14.78
3	16.82	13.74	22.33	17.02	17.48	20.38
4	18.93	28.60	19.37	22.92	22.45	12.71
5	16.08	17.63	16.39	19.00	18.96	32.63
6	21.18	19.32	17.34	15.39	19.44	18.67
7	29.89	12.62	17.49	19.81	18.18	28.79
8	13.06	20.56	19.87	19.10	18.25	17.38
9	12.95	16.70	20.68	13.53	17.96	17.35
10	9.76	34.79	16.30	12.80	12.32	29.61
11	14.77	19.37	13.00	17.40	21.77	27.33
12	15.00	22.83	14.56	13.93	22.30	15.29
13	14.85	19.36	23.60	11.26	11.56	29.04
14	13.42	14.07	24.24	20.48	28.09	23.06
15	15.46	16.94	23.95	15.39	17.00	17.97
16	10.48	20.28	14.25	18.36	23.19	22.32
17	13.72	9.26	18.91	17.54	12.87	15.36
18	36.95	14.72	25.15	20.07	13.55	16.27
19	27.77	13.81	13.93	11.57	25.31	24.05
20	31.23	18.61	19.69	14.98	18.72	20.30
21	20.62	13.13	17.01	15.26	10.11	22.58
22	11.52	24.50	18.51	23.35	19.54	13.98
23	28.47	22.94	16.95	20.82	13.37	23.64
24	14.48	22.12	14.32	13.67	17.28	16.92
25	14.12	16.95	16.78	16.37	16.03	16.53
26	17.70	18.13	18.82	19.87	16.68	37.61
27	21.98	24.00	15.72	12.93	25.95	20.55
28	17.33	19.46	15.56	19.51	15.97	8.89
29	19.06	17.96	13.39	15.99	22.10	16.13
30	22.75	19.61	25.19	14.72	18.12	24.64
31	16.07	22.05	10.60	20.32	21.36	21.88
Average	18.41	19.28	18.69	17.25	18.41	20.74
SD	6.79	5	5.35	3.72	4.28	6.33

Table B-27: Effect of the Variability of the G&D Hollow-spindle Machine on the Number of Bouclé Profiles per Decimetre

Sample	Yarn 1	Yarn 2	Yarn 3	Yarn 4	Yarn 5	Yarn 6
1	17	14	10	14	13	15
2	18	15	17	14	15	13
3	15	16	12	18	13	17
4	13	16	17	15	11	15
5	15	19	14	13	16	14
6	16	14	15	15	16	20
7	13	12	14	14	13	19
8	13	17	19	14	18	17
9	16	17	16	12	14	15
10	15	14	18	19	12	18
11	13	18	18	16	20	20
12	16	10	15	16	16	16
13	13	19	15	4	18	16
14	15	13	16	15	15	14
15	12	15	17	12	16	16
Average	14.67	15.20	15.5	14.07	15.07	16.33
SD	1.7	2.5	2.3	3.39	2.46	2.16

Table B-28: Effect of Interction between the Bending Stiffness of the Core Thread and the Bending Stiffness of the Effect Thread on the Size of Bouclé Profile (mm^2)

Sample	Standard Trial Order and Yarn Designation								
	St. 1	St. 2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8	St. 9
	Yarn C1&E1	Yarn C1&E2	Yarn C1&E3	Yarn C2&E1	Yarn C2&E2	Yarn C2&E3	Yarn C3&E1	Yarn C3&E2	Yarn C3&E3
1	11.80	15.68	17.06	13.61	11.43	18.99	15.14	15.20	17.16
2	9.38	13.18	19.55	15.63	9.88	8.94	11.11	8.15	9.24
3	9.46	9.49	11.35	8.38	9.14	11.35	21.88	6.51	8.15
4	8.59	11.97	16.22	6.62	7.64	9.89	9.44	10.83	11.16
5	13.40	14.51	19.30	12.56	11.12	16.68	12.00	7.51	15.49
6	12.73	11.63	8.73	12.19	7.06	17.76	10.25	16.37	21.33
7	8.65	11.81	10.99	12.65	8.56	15.13	12.63	11.15	17.43
8	6.58	8.98	16.26	10.12	8.85	11.38	8.85	9.83	11.40
9	8.75	14.04	24.49	17.33	13.48	15.74	8.44	15.40	12.42
10	12.37	8.60	13.28	10.52	8.35	13.99	10.94	8.36	13.89
11	9.67	14.97	8.52	10.23	10.95	13.96	8.13	13.70	14.62
12	9.36	15.06	16.81	11.51	12.79	11.95	20.57	8.64	13.62
13	13.97	10.55	28.54	10.67	24.38	17.21	9.54	7.71	16.49
14	9.33	13.46	13.16	9.96	7.37	20.19	19.11	6.16	11.68
15	8.25	6.23	17.04	7.40	12.63	8.08	14.47	8.38	16.29
16	7.72	8.59	11.23	7.22	9.18	15.14	9.82	6.97	13.81
17	11.62	7.90	14.51	9.12	7.12	15.52	14.02	16.25	12.72
18	12.57	11.73	12.15	8.35	12.60	27.20	9.12	11.04	7.80
19	16.67	14.83	22.49	6.10	14.64	9.42	11.86	9.61	17.23
20	9.26	16.28	9.32	10.38	8.74	13.67	13.26	8.54	14.61
21	8.38	18.20	12.01	8.10	10.24	21.40	10.91	7.92	11.89
22	6.71	7.58	16.38	8.15	8.03	15.77	11.78	15.39	10.05
23	8.29	10.14	12.34	7.15	10.56	12.40	10.89	8.64	12.88
24	11.50	13.32	15.46	9.26	8.02	12.32	7.86	7.16	10.83
25	8.15	11.87	8.33	9.46	11.77	17.42	13.85	12.03	10.27
26	9.58	12.90	18.24	7.70	10.11	19.55	7.13	11.10	12.60
27	7.15	8.18	15.05	12.75	12.11	13.52	16.45	12.59	12.51
28	15.48	12.66	12.17	8.43	8.70	8.86	9.87	11.63	8.51
29	9.38	8.09	12.42	7.56	12.19	7.51	11.61	8.80	11.08
30	13.32	17.21	17.79	7.24	8.44	9.10	12.54	6.89	13.77
31	11.10	10.23	13.47	8.37	12.23	8.70	9.54	9.00	16.88
Average	10.29	11.93	14.98	9.83	10.59	14.15	12.03	10.24	13.15
SD	2.55	3.09	4.66	2.67	3.28	4.54	3.60	3.06	3.13

Table B-29: Effect of Interction between the Bending Stiffness of the Core Thread and the Bending Stiffness of the Effect Thread on the Number of Bouclé Profiles per Decimetre

Sample	**Standard Order of Trial and Yarn Designation**								
	St. 1	**St. 2**	**St. 3**	**St. 4**	**St. 5**	**St. 6**	**St. 7**	**St. 8**	**St. 9**
	C1&E1	**C1&E2**	**C1&E3**	**C2&E1**	**C2&E2**	**C2&E3**	**C3&E1**	**C3&E2**	**C3&E3**
1	24	18	9	18	12	13	28	20	13
2	18	13	11	23	16	13	24	18	15
3	23	11	7	22	16	16	24	21	15
4	27	15	9	16	12	11	14	17	14
5	22	11	14	16	19	8	25	20	12
6	20	13	7	11	14	12	18	18	12
7	21	10	6	10	17	11	13	31	9
8	21	13	10	21	13	12	19	17	13
9	17	11	13	13	13	10	25	14	9
10	18	14	10	19	14	7	22	19	12
11	19	9	11	13	17	8	20	15	11
12	18	12	8	14	15	7	13	15	18
13	19	18	9	16	18	5	27	15	8
14	21	11	8	20	17	11	20	15	9
15	21	12	12	18	15	5	20	13	7
Average	20	12.7	9.6	16.6	15.2	9.9	20	17.8	11.8
SD	3.4	2.6	2.3	3.9	2.1	3.1	4.8	4.3	3

Table B-30: Results of Confirmation Trials for Effect of Interction between the Bending Stiffness of the Core Thread and the Bending Stiffness of the Effect Thread

Sample	Size of Bouclé Profiles (mm^2)		Number of Bouclé Profiles (dm^{-1})	
	Confirmation Yarn 1	Confirmation Yarn 2	Confirmation Yarn 1	Confirmation Yarn 2
1	14.91	14.33	13	13
2	20.52	16.04	15	9
3	11.69	15.87	18	11
4	11.68	13.29	11	9
5	11.80	16.12	18	11
6	13.12	11.91	9	12
7	8.74	9.31	12	11
8	14.96	11.46	14	14
9	11.36	18.55	7	10
10	15.11	19.45	6	12
11	9.01	11.16	15	14
12	13.24	10.61	13	13
13	10.65	18.86	15	10
14	10.49	13.62	12	21
15	10.96	14.09	13	18
16	10.07	14.09		
17	15.17	12.33		
18	13.81	14.92		
19	8.77	10.11		
20	8.94	16.66		
21	15.87	8.99		
22	14.51	12.59		
23	12.06	10.04		
24	9.14	20.34		
25	12.64	10.94		
26	10.11	9.86		
27	12.64	11.46		
28	12.47	11.30		
29	11.29	9.62		
30	15.62	14.16		
31	7.99	12.02		
Average	12.235	13.35	11.8	12.7
SD	2.748	3.15	3	3.4

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